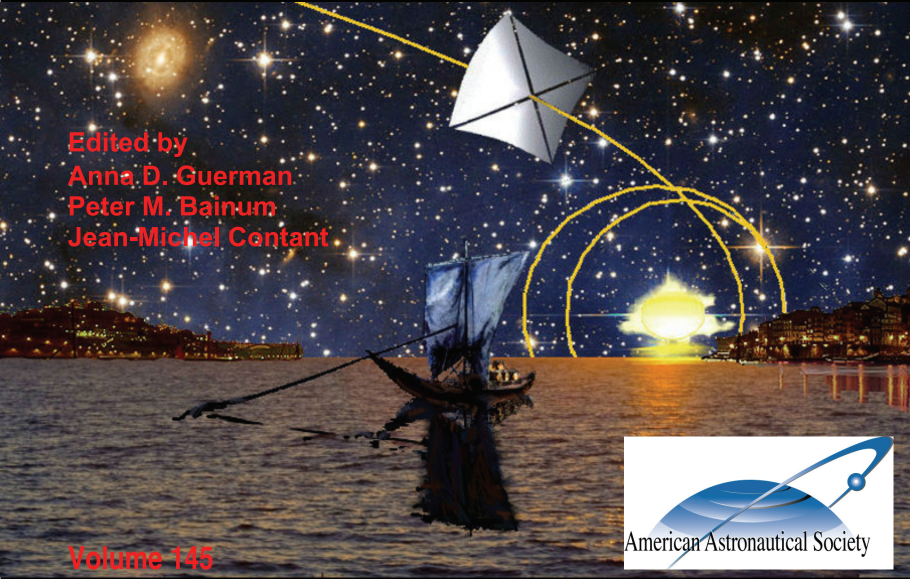
First IAA Conference on DYNAMICS AND CONTROL OF SPACE SYSTEMS 2012



Edited by
Anna D. Guerman
Peter M. Bainum
Jean-Michel Contant

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American Astronautical Society

ADVANCES IN THE ASTRONAUTICAL SCIENCES

DYNAMICS AND CONTROL OF SPACE SYSTEMS
DyCoSS'2012

EDITORS
Dr. Anna D. Guerman | University of Beira Interior, Portugal
Dr. Peter M. Bainum | Howard University, U.S.A.
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Robert H. Jacobs | Univelt, Incorporated, U.S.A.

Front Cover Illustration:

Portugal, a country with a long history of sailing, navigation, and discoveries of new frontiers, welcomes the 1st IAA conference on Dynamics and Control of Space Systems.
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FOREWORD

The first IAA Conference on Dynamics and Control of Space Systems – DyCoSS'2012 was held in Porto, Portugal in the Hotel HF Ipanema Porto on March 19–21, 2012 with the aim to join specialists in Astrodynamics, Space Flight Mechanics, and Space Structures. The Conference was organized by the International Academy of Astronautics (IAA) with the cooperation of the American Astronautical Society (AAS). The conference Chairs are Anna D. Guerman (Portugal), Peter M. Bainum (USA), and Jean-Michel Contant (France). Its International Program Committee consisted of:

- Kyle Terry Alfriend, USA
- Hyochoong Bang, Korea
- Franco Bernelli, Italy
- James D. Biggs, UK
- Jeng-Shing Chern "Rock", Taiwan
- Bernd Dachwald, Germany
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- Michael Ovchinnikov, Russia
- Maria Rosario Pinho, Portugal
- Antonio Bertachini Prado, Brazil
- Georgi V. Smirnov, Portugal
- David B. Spencer, USA
- Paolo Teofilatto, Italy
- Zhang Wei-Hua, China

The local organization was supported by the Centre for Aerospace Science and Technologies of the University of Beira Interior, Covilha (CAST-UBI), and the Engineering Faculty of the Porto University, Portugal (FEUP) with the following Local Organizing Committee:

- Anna D. Guerman, CAST-UBI, coordinator
- Margarida Ferreira, FEUP, coordinator
- Maria Rosario Pinho, FEUP
- Georgi Smirnov, University of Minho, Portugal
- Miguel Ângelo Silvestre, CAST-UBI
- Nikolai Danylchyk, technical support.

The total number of submissions surpassed all expectations, achieving 183 abstracts from 23 countries from Europe, Asia, Africa and America (only Australia and Antarctica were not represented). After the review process, 155 papers were accepted for presentation. These papers were organized in 15 thematic sessions; with 10–11 papers in each session. The final program consisted of 138 presentations, though during the conference only 107 papers have been actually presented by the authors, others being late withdrawals or "no show." The present book includes only the papers that have been discussed at the DyCoSS'2012 sessions.

The Opening Session began with a brief introduction of the conference by Anna Guerman and the welcome message from Prof. Peter Bainum who could not be present in person, so his message was read by Prof. Kathleen Howell. The second speech was delivered by Dr Antonio Neto da Silva, President of Proespaço—the Portuguese Association of Space Industries, who informed the audience of the Proespaço proposal for the Portuguese national strategy for the space industry. Finally, Dr. Jean-Michel Contant, the Secretary General of the International Academy of Astronautics presented a talk "The International Academy of Astronautics and Astrodynamics: Fifty Years of Excellence." All contributions caused a great interest among the public.

The Opening Session was followed by the Keynote Lecture of Dr. Constantinos Stavrinidis, Head of Mechanical Engineering Department of ESA-ESTEC, titled "Dynamics and Control of Space Systems." The presentation was dedicated to the modern problems in space systems dynamics that arose in the development of ESA missions.

The work of thematic sessions of DyCoSS'2012 began in the afternoon of March 19 and continued to the afternoon of March 21. These sessions included presentations on Attitude Dynamics and Control (3 sessions), Attitude Sensors and Actuators, Guidance, Navigation and Control (3 sessions), Mission Design and Optimization (2 sessions), Optimal Control in Space Flight Dynamics, Orbital Dynamics and Determination (2 sessions), Satellite Constellations and Formation Flying (2 sessions), and Space Structures and Tethers.

The Conference DyCoSS'2012 was followed by a satellite event, 7th International Workshop and Advanced School "Spaceflight Dynamics and Control" organized by CAST-UBI and FEUP at the Engineering School of the Porto University on March 22-23, 2012. The Advanced School web page (www.aerospace.ubi.pt/workshop2012) contains the detailed information on the event, as well as the presentations made by the participants.

The 1st IAA Conference on Dynamics and Control of Space Systems attracted an unexpectedly large number of scientists from all over the world, and provided interesting forum for research in the field. It contributed to intensive discussions of the modern research, dissemination of the up-to-date information in the area and better contacts between the members of Space Systems scientific community. DyCoSS found its place in the tight calendar of the events in Space Systems and we are confident that this first edition will be followed in the near future by the respective series of DyCoSS conferences.

Nothing of the above would be possible without great effort of many colleagues. We are most grateful to all members of the International Program Committee, the Local Organizing Committee and several dedicated volunteers that helped us to organize DyCoSS'2012. We appreciate very much the hard work of the participants of DyCoSS'2012 (both the authors of papers and the audience in general) that made possible fruitful discus-

sions at the conference sessions and beyond. Finally, we would like to express our gratitude to Mr. Robert Jacobs for his continuous support and to the Univelt, Inc., for publishing this volume.

Dr. Anna D. Guerman
University of Beira Interior
Covilhã, Portugal
DyCoSS'2012 Co-Chair

Dr. Peter M. Bainum, P.E.
Howard University
Washington, D.C., U.S.A.
DyCoSS'2012 Co-Chair

Dr. Jean-Michel Contant
International Academy of Astronautics
Paris, France
DyCoSS'2012 Co-Chair

OPENING MESSAGE

Opening Message by Peter M. Bainum, Co-Chair for IAA DyCoSS and Member, Program Committee, Read by Dr Kathleen C. Howell, Purdue University:

I would like to thank my colleague Dr Kathleen Howell, Purdue University for kindly consenting to read out these Opening Comments on my behalf during the Opening Ceremony for the First IAA DyCoSS.

I am still recovering from foot surgery last Fall and under medical advice and unable to travel to Porto to participate in the first IAA Conference on the Dynamics and Control of Space Systems. I would like to thank my colleague, Dr Anna Guerman for her inspiration and idea for organizing this very first Conference ever for the IAA DyCoSS. AppreciatIon is also extended to Dr Jean-Michel Contant, Secretary General of the IAA, for his help and for serving as co-chair of the IAA DyCoSS Program Committee. The American Astronautical Society and Mr. Robert Jacobs have agreed to publish the Full Proceedings of the Conference in the AAS *Advances of the Astronautical Sciences*. Selected papers will also appear in a Special Issue of *Acta Astronautica*.

Thanks are extended to the many participants of the conference and for all their work in preparing such a large number of papers, agreeing to co-chair the three parallel technical sessions over a three day period, as well as those who are serving in the DyCoSS Program Committee. The Local Organizing Committee is responsible for the famous Portuguese hospitality, and finally the DyCoSS will be followed by a Workshop and Advanced School “Space Flight Dynamics and Control”organized at the Engineering School at the Porto University on March 22–23, 2012 which should be of interest to many students who can interact with the professionals.

My best wishes for the success of both events and my sincere apologies for not being able to join many friends and colleagues during these days.

Peter M. Bainum
Distinguished Prefessor, Emeritus
Howard University
Washington, D.C., U.S.A.

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THE PROESPAÇO PROPOSAL

National Strategy for the Space Sector: Proposals Made By Proespaço, The Portuguese Association of Space Industries
March 19, 2012

António Neto da Silva, President of Proespaço, the Portuguese Association of Space Industries, Portugal

Portugal's space industry is currently at an intermediate stage of development. The objectives for growth in its industrial base, technical skills and technological development set out in the Strategy for 2005–2008 were achieved in every area and a 100% geographical return was accomplished in optional program.

We recommend that Portugal consolidate the idea of how it wants to develop the space sector based on the following goals: (1) creating a modern industrial sector that is both profitable and engaged in international projects; (2) creating an international image of industrial and scientific excellence; (3) promoting innovation and integrating value chains related to navigation, telecommunications and earth observation, which would necessarily include the greater added value aspects of these sectors; (4) using the space industry as a tool for administrative modernization, particularly in regard to territorial planning (continental and oceanographic), natural resources management, civil protection, and environmental and climate change monitoring; and (5) using space as a means of cooperating with other Portuguese-speaking countries.

In this way, Portugal should reach a level of technological maturity in the next decade that will establish the country as an upstream supplier of small integrated systems and subsystems for space missions, including scientific instrumentation (for both the earth and space segments). [View Full Paper]

SESSION 1: ATTITUDE DYNAMICS AND CONTROL I

Chairs: Richard W. Longman, Columbia University, U.S.A.
Yasuhiro Morita, ISAS/JAXA, Japan

IAA-AAS-DyCoSS1-01-01
AAS 12 – 301

The Contribution of Thermal Effects to the Acceleration of the Deep-Space Pioneer Spacecraft

Orfeu Bertolami, Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal; and Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal;
Frederico Francisco, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal;
Paulo J. S. Gil, Departamento de Engenharia Mecânica and IDMEC – Instituto de Engenharia Mecânica, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal;
Jorge Páramos, Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade Técnica de Lisboa, Portugal.

A method for the computation of the radiative momentum transfer in the Pioneer 10 & 11 spacecraft due to the diffusive and specular components of reflection is presented. The method provides a reliable estimate of the thermal contribution to the acceleration of these deep space probes and allows for a Monte-Carlo analysis from which an estimate of the impact of a possible variability of the parameters. It is shown that the whole anomalous acceleration can be explained by thermal effects. The model also allows one to estimate the expected time evolution of the acceleration due to thermal effects. The issue of thermal conduction between the different components of the spacecraft is discussed and confirmed to be negligible. [View Full Paper]

IAA-AAS-DyCoSS1-01-02
AAS 12 – 302

Closed Form Integration of the Hitzl-Breakwell Problem in Action-Angle Variables

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As an alternative to recent efforts in giving a complete solution to the attitude propagation of a tumbling triaxial satellite under gravity-gradient, we reformulate the problem in action-angle variables. The new solution is computed by the Lie-Deprit approach and is given in closed form, either for the secular or periodic terms, therefore being valid for any triaxial satellite. Comparisons with other approaches in the literature using nonaction-angle variables show the efficiency of the new solution for a variety of test cases. [View Full Paper]

IAA-AAS-DyCoSS1-01-03
AAS 12 – 303
The Dynamics and Control of Axial Satellite Gyrostats of Variable Structure

Vladimir S. Aslanov, Theoretical Mechanics Department, Samara State Aerospace University, Samara, Russia

This paper presents the study of the dynamics and control of an axial variable structure satellite (asymmetric platform and an axisymmetric rotor). Inertia moments of the rotor change slowly over time. The dynamics of the satellite is described by using ordinary differential equations with Serret-Andoyer canonical variables. For undisturbed motion, the stationary solutions are found, and their stability is studied. The control law is obtained for the satellite with variable structure on the basis of the stationary solutions. By means of computer numerical simulations, we have shown that the motion of the satellite controlled by founded internal torque is stable. [View Full Paper]

IAA-AAS-DyCoSS1-01-05
AAS 12 – 304
Concise Form of the Dynamic and Kinematic Solutions of the Euler-Poinsot Problem

Marcello Romano, Mechanical and Aerospace Engineering Department, U.S. Naval Postgraduate School, Monterey, California, U.S.A.

The *spontaneous motion* (or torque-free motion) of a triaxial rigid body, also known as Euler-Poinsot motion, is defined as the rotation of a rigid body under no external torques. Previously known exact solutions of the Euler-Poinsot problem are here presented in an original form. The solutions for both the dynamics (angular velocity components) and for the kinematics (in terms of elements of the rotation matrix) are here presented as a sequence of self-contained theorems. In particular, the dynamic solution, discovered by Jacobi, is formulated in a new universal form which is advantageous with respect to previously proposed forms: in fact the new form proposed here is very compact and it is *universal*, in the sense that all of the possible cases of initial conditions and body geometries are treated in a single statement and no branching in different solutions, as a discrete function of time, is necessary. Furthermore, the kinematic solution in terms of rotation matrix, initially proposed by Jacobi, is re-written here in modern notation, and, for the first time, given in a universal form. The here proposed formulations, because of their compactness and universality, are appealing for use in both graduate students' education and in the engineering practice: in fact, they are particularly suitable for software implementation. [View Full Paper]

IAA-AAS-DyCoSS1-01-06
AAS 12 – 305
On Stability of Relative Equilibria for an Inverted Pendulum Attached to the Equator

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Relative equilibria of a pendulum attached to the equator of the rotating Earth are studied. The length of the inverted pendulum corresponding to change in the degree of instability is determined. Family of relative equilibria appearing with the change of the degree of instability is found, and the stability of these equilibria is investigated.

Everyday experience tells us that the inverted pendulum of a small length is unstable. The degree of instability in this case is equal to two, which means the pendulum topples for any small deviation from local vertical in any direction. However, as is known from investigations in dynamics of the so called orbital elevator,[1] the radial relative equilibria are stable in the Lyapunov sense for the inverted pendulum if its free end is located behind the geosynchronous orbit. In this case the degree of instability for this equilibrium equals to zero. By virtue of continuity there exist values of the inverted pendulum length such that its degree of instability is equal to one. Determination of a range of such lengths is one of the goals of this paper. Another goal relates to determination of oblique relative equilibria and investigation of their stability.

The relative equilibria and their stability are studied with the use of redundant Cartesian coordinates. They are described using with the Routh equation for the critical points of the Routh function. This description allows to easily determine the constraint reaction. [View Full Paper]

IAA-AAS-DyCoSS1-01-07
AAS 12 – 306
Stability of Spinning Satellite under Axial Thrust and Internal Mass Motion

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Jozef C. van der Ha, Consultant, Deming, Washington, U.S.A.

This paper considers a spinning rigid body and a particle with internal motion under axial thrust. This model is helpful for gaining insights into the nutation anomalies that occurred near the end of orbit injections performed by STAR-48 rocket motors. The stability of this system is investigated by means of linearized equations about a uniform spin reference state. In this model, a double root does not necessarily imply instability. The resulting stability condition defines a manifold in the parameter space. A detailed study of this manifold and the parameter space shows that the envelope of the constant solutions is in fact the stability boundary. Only part of the manifold defines a physical system and the range of frequency values that make the system unstable is restricted. Also it turns out that an increase of the spring stiffness, which restrains the internal motion, does not necessarily increase the stability margin. The application of the model is demonstrated using the orbit injection data of ESA's Ulysses satellite in 1990. [View Full Paper]

IAA-AAS-DyCoSS1-01-09
AAS 12 – 307

Modes of Motion of Soyuz Orbital Stage after Payload Separation at Carrying Out of Short-Term Research Experiments

I. V. Belokonov, Space Research Department, Samara State Aerospace University, Samara, Russia; **A. D. Storozh**, State Research and Production Space Rocket Center "TsSKB-Progress," Samara, Russia; **I. A. Timbay**, Samara State Aerospace University, Samara, Russia

The uncontrolled motion of Soyuz orbital stage after spacecraft separation is discussed. Two versions of motion are considered. The first variant is the stage motion after utilization of the jet nozzle; the second variant is the stage motion without utilization of a jet nozzle. The stochastic model of initial conditions of angular motion is formulated. The influence of the gravitational and the aerodynamic moments on the motion around its mass center is considered. Movement features of the orbital stage shown in preservation of certain angular orientation during time, sufficient for the successful decision of navigation-communication problems at carrying out of short-term research experiments on Soyuz carrier rocket orbital stage after separation of mail payload are revealed. [View Full Paper]

IAA-AAS-DyCoSS1-01-10
AAS 12 – 308

On-Board Autonomy for ISRO Geosynchronous Spacecraft

Vinod Kumar, **A. K. Kulkarni**, **K. Parameswaran**, **R. Pandiyan** and **N. K. Malik**, ISRO Satellite Centre, Bangalore-560017, India

Development of on-board autonomy using Fault Detection Isolation and Re-configuration (FDIR) and Emergency Sun Re-acquisition for the ISRO Geosynchronous Communication spacecraft is described. The communication satellites are always with ground contact to provide uninterrupted communication, mobile and Direct To Home (DTH) services. In order to ensure continuous availability of these services and to prevent the heavy loss of revenue in case of failures in AOCS equipments, the self healing or automatic FDIR functions to survive the hostile space environment, has been envisaged. The FDIR provides quick reaction to reconfigure the spacecraft automatically in case any AOCS equipment malfunctions and thus prevents any possible attitude loss.
Key Words: Fault Detection Isolation and recovery (FDIR), Emergency Sun Reacquisition (ESR), Attitude and Orbit Control System (AOCS), Infra Red Earth Sensor (IRES or ES), Attitude and Orbit Control Electronics (AOCE), Momentum Biased System, Station Keeping (SK) Mode, Self Healing Control System (SHCS), Data Freeze (DF), Data Ready (DR). [View Full Paper]

SESSION 2: ORBITAL DYNAMICS AND DETERMINATION I

Chairs: James Biggs, University of Strathclyde, Glasgow, UK
Filippo Graziani, Italy

IAA-AAS-DyCoSS1-02-01
AAS 12 – 309
Accelerometer Data Handling for the BepiColombo Orbit Determination

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In this work we consider the role of the non gravitational accelerations acting on the Mercury Planetary Orbiter of the BepiColombo mission and we show how to include the corresponding digital calibrations in the orbit determination and parameter estimation procedure developed for the Radio Science Experiment. The non gravitational perturbations simulated consist in the accelerations of the s/c due to the direct solar radiation pressure and to the radiation reflected and thermal diffused by Mercury. In reality, these effects will be measured by the Italian Spring Accelerometer. These data are considered as an input for the differential correction process and we associate to them a digital calibration, to be determined, in order to absorb the systematic noise these measurements are affected by. We introduce three different models for these parameters and we show the results corresponding to the determination of the initial conditions for the s/c, the gravity field of Mercury, the Love number k_2, the desaturation maneuvers and the calibrations themselves, obtained by means of a constrained multi-arc non linear least squares fit. [View Full Paper]

IAA-AAS-DyCoSS1-02-03
AAS 12 – 310
Towards Automated Determination of Orbit Maneuvers for GNSS Satellites

Gottlob Gienger, Research and Technology Management Office (HSO-GX), ESA/ESOC, Darmstadt, Germany;
Filipe Lopes Pereira, GMV S.A. - on contract at the European Space Agency, Navigation Support Office (HSO-GN), ESA/ESOC, Darmstadt, Germany

ESOC's navigation support office routinely performs precise orbit determination for GPS, GLONASS and Galileo navigation satellites. The orbit determination process including maneuvering satellites, using >500 station passes per satellite per day requires: (i) Automated search of station passes for orbit maneuvers (ii) Precise location of their start and end times (iii) Automated Delta-V estimation. Impulsive and non-impulsive maneuver models were tested on operational tracking data sets with Mathematica. The best performing algorithms were implemented into ESOC's Navigation Package for Earth Orbiting Satellites. Tests conducted on GPS orbit maneuvers 2011/2012 show very good agreement with the values published by Center for Orbit Determination in Europe. Delta-V maneuvers can now be identified within a few hours after their completion and duly considered in IGS products. [View Full Paper]

IAA-AAS-DyCoSS1-02-07
AAS 12 – 311
On the Sequential Solution of Elliptic Kepler's Equation

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The solution of elliptic Kepler equation $E - e \sin E = M$ is a classical problem of Celestial Mechanics with a long history. Most of the methods proposed in the literature are one-time methods in the sense that for a given $e \in [0, 1)$ and $M_0 \in [0, p]$ they attempt to provide an approximation of the unique solution $E_0 = E_e(M_0)$ of Kepler's equation with maximum accuracy and minimum computational cost. However as remarked recently by Mortari and coworkers in several papers, some applications of orbit propagation require the solution of Kepler's equation for a fixed eccentricity along several mean anomalies $\{M_j\}_{j\geq 0}$. In this context they have proposed several methods, referred to as sequential solution methods, that use the available information of the solution $E_k = E_e(M_k)$ at M_k to obtain the approximation $E_{k+1} = E_e(M_{k+1})$ at the next $M_{k+1} = M_k + \Delta M$. The aim of this paper is to propose new sequential solution methods. Further, numerical experiments comparing computational cost and accuracy with existing methods are presented. [View Full Paper]

IAA-AAS-DyCoSS1-02-08
AAS 12 – 312
Orbital Manoeuvres with Single-Input Control

Anna D. Guerman, Center for Aerospace Science and Technologies, UBI, Department of Electromechanical Engineering, University of Beira Interior, Covilhã, Portugal; **Georgi V. Smirnov**, Center of Physics, UM, Department of Mathematics and Applications, University of Minho, Campus de Gualtar, Braga, Portugal

We study the problem of orbital control under the constraints on the thrust direction for a nonlinear dynamical model. The satellite is equipped with a passive attitude control system providing one-axis stabilization and a propulsion system consisting of one or two thrusters oriented along the stabilized axis. Different applications, such as formation flying and satellite de-orbiting are considered. [View Full Paper]

IAA-AAS-DyCoSS1-02-10
AAS 12 – 313
Orbit-Attitude Perturbation of a Charged Spacecraft in the Geomagnetic Field

Hani M. Mohammed, Department of Solar and Space Research, NRIAG, Cairo, Egypt; **M. K. M. Ahmed** and **Ashraf H. Owis**, Department of Astronomy, Meteorology and Space Science, Faculty of Science, Cairo University, Giza, Egypt

In this work we investigate the orbit-attitude perturbations of a rigid spacecraft due to the effects of several forces and torques. The spacecraft is assumed to be of a cylindrical shape and equipped with a charged screen with charge density σ. Clearly the main force affecting the motion of the spacecraft is the gravitational force of the Earth with uniform spherical mass. The effect of oblate Earth up to J_2 is considered as perturbation on both the orbit and attitude of the spacecraft, where the attitude of the spacecraft is acted upon by what is called gravity gradient torque. Another source of perturbation on the attitude of the spacecraft comes from the motion of the charged spacecraft in the geomagnetic field. This motion generates a force known as the Lorentz force which is the source of the Lorentz force torque influencing the rotational motion of the spacecraft. In this work we give an analytical treatment of the orbital-rotational dynamics of the spacecraft. We first use the definitions of Delaunay and Andoyer variables in order to formulate the Hamiltonian of the orbit-attitude motion under the effects of forces and torques of interest. Since the Lorentz force is a non-conservative force, a potential like function is introduced and added to the Hamiltonian. We solve the canonical equations of the Hamiltonian system by successive transformations using a technique proposed by Lie and modified by Deprit and Kamel to solve the problem. In this technique we make two successive transformations to eliminate the short and long periodic terms from the Hamiltonian. [View Full Paper]

SESSION 3: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL I

Chair: Hyochoong Bang, KAIST, Daejeon, Korea

IAA-AAS-DyCoSS1-03-01

AAS 12 – 314

Hybrid Propulsion Transfers to the Moon

Giorgio Mingotti, Distributed Space Systems Laboratory, Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa, Israel;
Francesco Topputo and **Franco Bernelli-Zazzera**, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Milano, Italy

This work analyzes special Earth–Moon transfers that make use of both chemical and solar electric propulsion. A first high-thrust, low-I_{sp} impulse is used to place the spacecraft into an exterior-like low-energy transfer to the Moon, possibly performing a lunar gravity assist. The subsequent use of low-thrust, high-I_{sp} propulsion makes it possible to perform a lunar ballistic capture leading to a final, low-altitude orbit about the Moon. Hybrid propulsion transfers outperform both the chemical transfers (Hohmann, interior, and exterior) and the fully solar electric propulsion transfers (e.g., SMART-1-like) in terms of propellant consumption, although an assessment of these transfers at system level is still missing. [View Full Paper]

IAA-AAS-DyCoSS1-03-03

AAS 12 – 315

Nonlinear Control of Leader-Follower Formation Flying

Giuseppe Di Mauro, **Pierluigi Di Lizia**, **Roberto Armellin** and **Michèle Lavagna**, Aerospace Engineering Department, Politecnico di Milano, Milano, Italy

This paper considers the problem of relative motion control involved in a leader-follower formation keeping mission. More specifically, center of mass dynamics of two Earth orbiting satellite is modeled, including the nonlinearity due to Earth oblateness. Next, the differential algebra is exploited to compute an high order Taylor expansion of the State-Dependent Riccati Equation (SDRE) solution. This new approach reduces the computational cost of the online Algebraic Riccati Equation solution required by SDRE algorithm; in fact, the differential algebraic formulation gives a polynomial representation which can be directly evaluated for SDRE solutions or exploited to define an initial first guess for iterative SDRE algorithms. [View Full Paper]

IAA-AAS-DyCoSS1-03-04
AAS 12 – 316
Distant Orbits Around Mercury

Xue Ma, **Junfeng Li**, **Hexi Baoyin**, **Peng Zhang**, **Jingyang Li** and **Yang Chen**;
School of Aerospace, Tsinghua University, Beijing, China

For some low cost space missions to Mercury, distant orbits around the planet are studied. This research is carried out in the framework of the elliptic restricted three-body problem (ER3BP), because of the planet's non-negligible eccentricity. Two families of prograde and retrograde planar orbits in the CR3BP are chosen for their useful shapes or good performance of stability with high altitude, and we extend the study of these orbits to the ER3BP case. The stability of all above orbits around Mercury is investigated in this paper. Our research indicates that orbits within a large altitude range may keep certain shapes long enough for space missions. [View Full Paper]

IAA-AAS-DyCoSS1-03-05
AAS 12 – 317
Single-Axis Pointing of a Magnetically Actuated Spacecraft

Giulio Avanzini, Faculty of Industrial Engineering, University of Salento, Brindisi, Italy; **Emanuele L. de Angelis** and **Fabrizio Giulietti**, Department of Mechanical and Aerospace Engineering (DIEM), University of Bologna, Forlì, Italy

The use of magnetic actuators on Low Earth Orbiting spacecrafts represents an attractive solution because of its simplicity, reliability and a power-effective smooth modulation of control actions. Attitude regulation yet proves to be a challenging problem, since magnetic actuators alone do not allow providing three independent control torque components at each time instant. The goal of this paper is to derive a rigorous proof of global asymptotic stability for a magnetic control law that leads the satellite to a desired spin condition around a principal axis of inertia, pointing the spin axis towards a target direction in the inertial reference frame. [View Full Paper]

IAA-AAS-DyCoSS1-03-06
AAS 12 – 318
Nonlinear Filtering Methods for Spacecraft Navigation Based on Differential Algebra

Monica Valli, **Roberto Armellin**, **Pierluigi Di Lizia** and **Michèle R. Lavagna**,
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The nonlinear filtering problem plays an important role in various space-related applications and especially in orbit determination and navigation problems. Differential algebraic (DA) techniques are here proposed as a valuable tool to implement the higher-order numerical and analytic extended Kalman filters. Working in the DA framework allows us to consistently reduce the required computational effort without losing accuracy. The performance of the proposed filters is assessed on different orbit determination problems with realistic orbit uncertainties. The case of nonlinear measurements is also considered. Numerical simulations show the good performance of the filter in case of both complex dynamics and highly nonlinear measurement problems.
[View Full Paper]

IAA-AAS-DyCoSS1-03-10
AAS 12 – 319
Electric Solar Wind Sail Control and Navigation

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The electric solar wind sail is a propulsion system that uses long centrifugally spanned and electrically charged tethers to extract solar wind momentum for spacecraft thrust. The sail solar zenith angle and phase can be controlled by modulating the voltage of each tether separately to produce net torque for attitude control and thrust vectoring. In this paper, we cover the basics of the electric sail control based on our set of dynamical models including single tether simulation and rigid body and fully dynamical simulations for the entire sail. Short descriptions of these models are given. We also consider real solar wind conditions based on available solar wind data and address the effects of the solar wind density and velocity variations on the sail dynamics, control, and navigation. [View Full Paper]

SESSION 4: ATTITUDE SENSORS AND ACTUATORS

Chairs: Franco Bernelli, Politecnico di Milano, Italy
Michael Ovchinnikov, Keldysh Institute of Applied Mathematics, Moscow, Russian Federation

IAA-AAS-DyCoSS1-04-01
AAS 12 – 320

Tilted Wheel for Three-Axis Attitude Control of a Rigid Satellite

Lawrence O. Inumoh, **Nadjim Horri** and **Alex Pechev**, Surrey Space Centre, University of Surrey, Guildford, UK

Generation of control torque for highly agile satellite missions is generally achieved with momentum exchange devices, such as reaction wheels and control moment gyros (CMGs) with high slew manoeuvrability. However, the generation of a high control torque from the respective actuators requires high power and thus a large mass. This paper proposes a new type of control actuator that will be developed to generate torques in all three principal axes of a rigid satellite using only a reaction wheel and a simple tilt mechanism. The mechanism will rotate the spin axis of the wheel (tilt the angular momentum vector) about two additional axes thereby generating high control torque about the axes orthogonal to the wheel spin axis. Torque will also be generated about the wheel spin axis through the increase or decrease of the wheel speed. The newly proposed actuator generates control torque through controlled precession of the spinning wheel while the tilt angle and the tilt rates are computed without the use of the popular pseudo-inverse calculation obtained with CMGs leading to no singularities being experienced during nominal wheel operation. This paper describes the fundamental mathematical dynamic model of the system and an analysis of the torque and angular momentum envelopes as well as the singularities reached for this system. Numerical simulations are used to demonstrate the agile three-axis attitude control capability of this proposed actuator in a momentum bias control mode. This proposed actuator that generates torque in all three axes of a rigid satellite compared to other momentum exchange actuators (that require a minimum of three units) gives a reduction in mass and power consumption that is very critical for every space mission. [View Full Paper]

IAA-AAS-DyCoSS1-04-02
AAS 12 – 321
Analysis of Ambiguity Resolution Methods for Attitude Determination using GPS Carrier Phase Measurements

Leandro Baroni, Federal University of Jequitinhonha and Mucuri Valleys, Teófilo Otoni, MG, Brazil; **Hélio Koiti Kuga**, Space Mechanics and Control Division, INPE - National Institute for Space Research, São José dos Campos, SP, Brazil

A body orientation can be calculated if GPS measurements are collected simultaneously from three or more GPS antennas body-mounted properly. Carrier phase double differences are used as GPS measurements and the ambiguous integer number of cycles in such measurements must be determined. For algorithm speedup constraints steaming from the fixed antennas configuration geometry are imposed. Two algorithms were analyzed accomplishing real-time attitude determination. Euler angles and quaternion formulation were compared. The test baselines were separated 1 meter apart perpendicularly. The results showed that the accuracy of both methods is in the order of 0.1° to 0.2° or better, but CPU times are quite different. [View Full Paper]

IAA-AAS-DyCoSS1-04-03
AAS 12 – 322

Attitude Dynamics of a Small-Sized Satellite Equipped with Hysteresis Damper

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Aggressive appearance of small-sized satellites, involvement of spin-off companies and universities in this business has renovated an interest to passive attitude control systems (PACS) implementation and use. Within ideology of PACS the problem of a disturbed attitude motion damping has to be solved first. Among a set of techniques available to do that a hysteresis damper leads due to its simple design, reliability, stability of its characteristics in time, suitable allocation in a satellite structure. However, these advantages are counteracted by a requirement to provide a synthesis of the damper parameters with qualified mathematical analysis of the satellite attitude dynamics, accurate numerical or even laboratory simulation, thermo treatment of the damper, arrangement of the damper inside the satellite body and other engineering demands. The latter should be specified with constrains initiated by its small size and interaction of the damper with other auxiliary units onboard. First of all, a mathematical model of the magnetic hysteresis should be chosen from the models available or to be developed taking into account specific conditions of the damper use. Configuration of the damper, i.e. its shape, geometric and magnetic parameters, volume of the damper, its allocation etc. should be determined. In the paper the problems to be solved while a hysteresis damper for PACS is used are considered. The models of hysteresis which allow one to achieve a compromise between reality and descriptiveness of results obtained both analytically and numerically are given. Examples how to apply the technique for gravity-gradient and magnetic PACS development and design for miniature satellites accompanied by results of their attitude dynamics investigation are presented. Samples of nanosatellites with hysteresis damper where the proposed approach was used and satellites were launched are shown. [View Full Paper]

IAA-AAS-DyCoSS1-04-05
AAS 12 – 323
Micro-Sun-Sensor Performance Validation in Ground-Reproduced Orbital Conditions

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This paper deals with the large-FOV, micro-sun-sensor under development at the University of Naples. The sensor exploits a multi-hole mask to measure the sun line with high precision. Nevertheless, multi-spot operation exhibits failures near FOV borders, due to the uncertainty in the number of spots that can be reliably acquired. After a short description of the sensor concept, hardware model, and laboratory test equipment, this paper focuses on the latest upgrades of the sensor operation mode, aimed at getting reliable operation ability and improved precision over a wider FOV (at least 90x80 deg). Specifically, an original technique is implemented in which the sensor shutter-time is automatically adapted based on detected image intensity to improve precision near FOV borders. Results of the validation and performance assessment campaign of the upgraded operation mode executed with the ground facility are presented. In these tests sensor precision is characterized as a function of the separation of the illumination direction from FOV centre, showing that the upgraded operation mode allows getting high precision (about 0.001°) also near FOV borders.[View Full Paper]

IAA-AAS-DyCoSS1-04-06
AAS 12 – 324
A Dynamic Friction Model for Reaction Wheels

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This paper addresses the problem of the bearing friction in a reaction wheel and applies a dynamic friction model in the current control loop. The dynamic friction model assumes that there are elastic bristles in the contact surfaces that bends when slipping forces are applied. The bristle behavior mimics the Stribeck effect without discontinuities. Some experiments were carried out in order to collect the necessary data to estimate the model parameters, using different control profiles in both current and velocity so as to emphasize a particular parameter. Least squares curve fitting was firstly employed to obtain viscous and Coulomb friction coefficients, while a Kalman filter estimated the break-away torque for a Stribeck friction model as well as viscous and Coulomb. Finally, an Extended Kalman Filter (EKF) was used to obtain some parameters of a LuGre dynamic friction model. Results of the filtering process are presented, thus asserting that dynamic friction models can be estimated with EKF provided the necessary conditions for sensor accuracy are met. [View Full Paper]

IAA-AAS-DyCoSS1-04-07
AAS 12 – 325
On Ground Calibration of Tetrahedron Gyro Package for Attitude Determination

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This work presents the on ground calibration of a gyro package composed of four fiber optic gyros in a tetrahedron configuration. In this work the on ground calibration is performed with a 3-axis turn table covering the work range of the chosen gyros. Analysis covering both the uncalibrated and calibrated accumulated attitude determination error are shown. An Allan variance analysis is performed in order to detect the main sources of noise and to improve the mathematical model. The calibration procedures developed in this work could be used in tests of an in-house tetrahedron geometry of the FOG unit that will fly in next Brazilian missions. [View Full Paper]

IAA-AAS-DyCoSS1-04-09
AAS 12 – 326
A MEMS-Based Multi-Sensor System for Satellite High-Accuracy Attitude Determination

Igor V. Merkuryev, Theoretical Mechanics & Mechatronics Department, Moscow Power Engineering Institute, Moscow, Russia

This paper deals with satellite attitude determination based on optimal fusion of microelectromechanical vibratory gyroscope measurements and star trackers by stochastic filtering. One of the ways to improve performances of micromechanical vibratory gyroscopes is to analyze their dynamics and errors in order to find efficient methods of digital signal processing. New nonlinear dynamic properties of electrostatically actuated microstructures are studied. Results of bench tests of the integrated navigating system of the small satellites are presented. [View Full Paper]

IAA-AAS-DyCoSS1-04-10

AAS 12 – 327

Model-Based Discrete PID Controller for CubeSat Reaction Wheels Based on COTS Brushless DC Motors

Teun Hoevenaars, **Steven Engelen** and **Jasper Bouwmeester**, Space Systems Engineering, Delft University of Technology, Delft, The Netherlands

With an increasing emphasis on the pointing capability of CubeSats, it is expected that a growing number of CubeSats will have reaction wheels as part of their Attitude Determination and Control System. Reaction wheels based on Commercial Off-The-Shelf Brushless Direct Current motors are well-suited for integration in CubeSats due to the small size, low power consumption and good dynamic response of these motors. This paper develops a discrete, model-based PID controller for a single reaction wheel which relies on Hall sensor measurements only to regulate the power available to the motor. Torque control is implemented using a ramp function for the reference rotation speed and the resulting controller is optimized for implementation in a microcontroller. With the Delfi-n3Xt reaction wheels as example, simulations are performed that illustrate the effectiveness of the developed controller to generate the commanded torque. [View Full Paper]

SESSION 5: MISSION DESIGN AND OPTIMIZATION I

Chairs: Kathleen C. Howell, Purdue University, West Lafayette, Indiana, U.S.A.
Rock Jeng-Shing Chern, China University of Science and Technology, Henshan Village, Hsinchu County, Taiwan, ROC

IAA-AAS-DyCoSS1-05-01
AAS 12 – 328

Reference Attitude Deriving Algorithm for Multistrip Imaging in Highly Agile Spacecrafts

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The computation of time varying image-motion plane and derivation of reference attitude is the main requirement of high resolution optical imaging for driving the spacecraft platform motion. In this paper, two types of imaging modes are considered. In Type-I imaging, the Image Plane is constructed perpendicular to the direction of imaging while in Type-II imaging the Image Plane is made parallel to the direction of imaging. Type-I imaging mode is applicable to a camera system where linear CCDs are used and the platform attitude should need to be controlled such that the projection of the linear CCD on ground is always maintained perpendicular to the imaging direction. Type-II imaging is applicable to a camera system wherein an area array CCD (e.g. TDI – Time Delay and Integration device) is used to improve overall Signal to Noise ratio. In such a case, the earth rotation compensation becomes a must in order to allow all the stages of the array to capture the signal from the same ground region before getting integrated. Spherical geometry is used to define the trajectory of imaging using two points in the desired direction on the earth surface where the earth model is built as an ellipsoid. Once the trajectory is defined, the image plane is constructed depending on the type of imaging. Using the image plane definition at each time and vector coordinate transform methods the platform attitude is derived. The paper has been arranged in four Sections viz., Section 1 describing the trajectory formation, Section 2 describing the image plane definition, Section 3 discussing about the attitude derivation at each time and the Section 4 focusing on the various ways of acquiring images using the defined attitude in the context of multi-strip imaging during a payload pass for a cartographic satellite, Cartosat-2. [View Full Paper]

IAA-AAS-DyCoSS1-05-05
AAS 12 – 329
Venus Transfers Design Combining Interplanetary Superhighways and Low–Thrust Arcs

C. Finocchietti, **P. Pergola** and **M. Andrenucci**, Aerospace Engineering Department, University of Pisa, Italy

The design of interplanetary trajectories based on patched circular restricted three body models is gradually becoming a valuable alternative to the classical patched conic approach. The main advantage offered by such a model is the possibility to exploit the manifold dynamics to move naturally far from or toward a body. Generally, propulsive maneuvers are required to match these structures. Low-thrust arcs offer the possibility to have a significant propellant mass reduction when moving from manifold to manifold. The aim of this paper is to present a methodology to design low-thrust orbit-to-orbit trajectories. The approach aims at identifying those trajectories inside the manifold image on a given Poincarè sections and at exploiting their transit behavior. The target value of the Jacoby constant is chosen as stop condition for the thrusting phases and coasting arcs are considered up to obtain the proper Poincarè section intersection. A grid search for an Earth to Venus transfer is presented as test case. [View Full Paper]

IAA-AAS-DyCoSS1-05-06
AAS 12 – 330
Design of Low Thrust Transfers to Libration Point Periodic Orbits Exploiting Manifold Dynamics

P. Pergola, **C. Finocchietti** and **M. Andrenucci**, Aerospace Engineering Department, University of Pisa, Italy

In this study we propose and analyse a mission scenario based on Electric Propulsion systems to accomplish space missions toward libration periodic orbits. The aim is to investigate about the feasibility, advantages and drawbacks deriving from utilizing an Electric Propulsion system in the context of the Circular Restricted Three Body Model. A complete GTO to Earth-Sun Halo orbit transfer is designed by considering the Euclid mission as reference. Modifying neither the spacecraft configuration nor the target orbit the original mission scenario is re-visited to deliver the same final mass with a smaller launch mass. Approximately 140 kg of propellant mass saving can be obtained and a direct launch avoided, but a longer transfer time (approximately thirty months instead of one) is required. The first guess generation process and the following optimization procedure are here presented for a minimum mass transfer that combines low-thrust arcs and manifold dynamics to reach the final three dimensional libration point periodic orbit. [View Full Paper]

IAA-AAS-DyCoSS1-05-07
AAS 12 – 331
Kinematic Attitude Maneuvers with Path Constraints for ASTROSAT: An Indian Astronomy Satellite

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Astronomy satellites carry sensitive instruments onboard for celestial observations. These instruments should not see bright objects such as Sun, Moon and Earth albedo while undergoing maneuvers. ASTROSAT is an Indian ASTROnomy SATellite with instruments having capability of observing celestial objects in multi-wavelength. ASTROSAT carries 5 payloads: (i) Ultra-Violet Imaging Telescope (UVIT) which operates in three wavelengths namely Far Ultra-Violet, Near Ultra-Violet and Visible bands, (ii) Soft X-ray Telescope (SXT), (iii) Large Area X-ray Proportional Counters (LAXPC) having total area of 6400 sq. Cms, (iv) Cadmium Zinc Telluride Imager (CZTI) and (v) Scanning Sky Monitor (SSM). In this, UVIT, SXT and SSM should avoid bright objects while the spacecraft maneuver from one celestial object to another. In this paper, a simple maneuver strategy developed to avoid bright Sun while maneuvering the spacecraft when the satellite is not in radio contact has been described. The Sun constraint of the instruments as well as the star sensors during observation is met using a pre-conceived definition of the spacecraft axes. However, during maneuver, the instruments are kept away from Sun to avoid damage and the Star sensor is allowed to pass through Sun quickly. The procedure is tested for various combinations of the celestial objects in order to ascertain that the method works without fail. Finally, the procedure has been planned for implementation onboard ASTROSAT in order to have the autonomy of operations of the satellite. [View Full Paper]

IAA-AAS-DyCoSS1-05-08
AAS 12 – 332
Libration Point Orbits Characterization in the Earth-Moon System for Scientific Applications

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Recently, a new effort has been reserved to explore the lunar environment with missions aimed at orbiting the Moon and collecting great amounts of data in view of a future human installation. In this context, several authors proposed the exploitation of periodic orbits around the equilibrium point L_1 in the Earth–Moon system with different objectives. The purpose of this study is to provide effective criteria that can be applied to choose a nominal orbit operable to these ends. We consider as key parameters lunar surface coverage, solar eclipses and orbit maintenance costs. We analyze a set of periodic and quasi-periodic orbits at different energy levels and we provide parametric analyses that can be used to identify a specific orbit according to the mission constraints.
[View Full Paper]

IAA-AAS-DyCoSS1-05-09
AAS 12 – 333
Design of Transfers Trajectories between Resonant Orbits in the Restricted Problem with Application to the Earth-Moon System

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The application of dynamical systems techniques to mission design has demonstrated that employing invariant manifolds and resonant flybys enables previously unknown trajectory options and potentially reduces the ΔV requirements. An analysis of two- and three-dimensional resonant orbits in the Earth-Moon system, as well as the computation and visualization of the associated invariant manifold structures is explored in this investigation. Three-dimensional maps are used to explore the relationship between the manifold trajectories associated with multiple resonant orbits and Earth departure trajectories. As a result, planar and three-dimensional homoclinic- and heteroclinic-type trajectories between unstable periodic resonant orbits are identified in the Earth-Moon system. To further illustrate the applicability of 2D and 3D resonant orbits in preliminary trajectory design, two planar transfers to the vicinity of L_5 and an out-of-plane transfer to a 3D periodic orbit that tours the entire Earth-Moon system are constructed exploiting the invariant manifolds associated with orbits in resonance with Moon. [View Full Paper]

IAA-AAS-DyCoSS1-05-10
AAS 12 – 334
Earth-Moon Libration Stationkeeping: Theory, Modeling, and Operations

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Collinear Earth-Moon libration points have emerged as locations with immediate applications. These libration point orbits are inherently unstable and must be controlled at a rapid frequency which constrains operations and maneuver locations. Station-keeping is challenging due to short time scales of divergence, effects of large orbital eccentricity of the secondary body, and third-body perturbations. Using the Acceleration Reconnection and Turbulence and Electrodynamics of the Moon's Interaction with the Sun (ARTEMIS) mission orbit as our platform (hypothesis), we contrast and compare promising stationkeeping strategies including Optimal Continuation and Mode Analysis that achieved consistent and reasonable operational stationkeeping costs. Background on the fundamental structure and the dynamical models to achieve these demonstrated results are discussed along with their mathematical development. [View Full Paper]

SESSION 6: SATELLITE CONSTELLATIONS AND FORMATION FLYING I

Chairs: Georgi Smirnov, University of Minho, Campus de Gualtar, Braga, Portugal
Gerard Gómez, University of Barcelona, Spain

IAA-AAS-DyCoSS1-06-01
AAS 12 – 335
Effects of Eccentricity of the Parent Body on Multi-Tethered Satellite Formations

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This paper discusses the relevance of eccentric reference orbits on the dynamics of a tethered formation, when a massive cable model is included in the analysis of a multitethered satellite formation. The formations examined in this study are Hub-And-Spoke (HAS) and Closed-Hub-And-Spoke (CHAS) configurations for in-plane and Earth-facing spin planes. A stability analysis is performed, together with the evaluation of the effects of eccentricity on tether elongation, agents relative position, and formation orientation and shape. The possible presence of periodic solutions is also investigated. [View Full Paper]

IAA-AAS-DyCoSS1-06-02
AAS 12 – 336
J_2-Perturbation Solution to the Relative Motion Problem

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A solution to the satellite relative motion problem is constructed based on a radial intermediary of the J_2-problem. The new solution accounts for non-linearities of the model to a high extent, and hence is adequate for long-term prediction of bounded relative orbits with arbitrary inclinations without limiting to the case of tightly-controlled formations. The integrability of the radial intermediary is utilized for finding periodic relative orbits in a local-vertical local-horizontal frame and to determine an initialization scheme that yields long-term boundedness of the relative distance. [View Full Paper]

IAA-AAS-DyCoSS1-06-04
AAS 12 – 337

A Comparative Study of Dynamics Models and a Control Strategy for Satellite Formation Flying

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In recent years, dynamics and control of satellite formations have been an active area of research. In the first part of this paper, a simulation method with a modeling error index is introduced to compare seven widely used dynamics models with a precise propagator. This evaluation is carried out by analyzing the effects of main error sources such as eccentricity of the reference orbit, formation size, inclination and gravitational perturbations in low Earth orbits. By means of the obtained numerical results, one may be able to choose the appropriate dynamics model according to the desired accuracy for a given mission. In the second part, a control strategy based on Lyapunov functions is undertaken to be applied on the nonlinear dynamics model. Applicability of this control method to bring and keep the deputy and chief satellites to a prescribed proximity is investigated while the deputy is under the uncertainty of initial conditions. The results illustrate the effectiveness of the presented control strategy. [View Full Paper]

IAA-AAS-DyCoSS1-06-06
AAS 12 – 338

Autonomous Decentralized Coordination Control for Fractionated Spacecraft Formation Reconfiguration Based on Cyclic Pursuit Strategy

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The current paper investigates the decentralized coordination control problem of fractionated spacecraft and proposes a new concept of finite-time cyclic pursuit algorithm for its practical implementation. Firstly, the relative translational dynamics of fractionated spacecraft and the general formation configuration description method are proposed, and the algebraic graph theory is introduced. Then, three-dimensional finite-time cyclic pursuit algorithms are put forward for both single-integrator kinematics and double-integrator dynamics, which guarantee the convergence of tracking errors in finite time rather than in the asymptotic sense. Finally, numerical simulations on finite-time cyclic pursuit algorithms and formation reconfigurations based on cyclic pursuit strategies are carried out. The simulation results have demonstrated the superior performance of finite-time cyclic pursuit algorithms, including the global fast convergence of tracking errors in finite time and the higher tracking accuracy. Moreover, the cyclic pursuit control is a very promising technique for fractionated spacecraft free flying, because it is leaderless, easy for implementation, and most important of all, it only requires the local information for control. [View Full Paper]

IAA-AAS-DyCoSS1-06-08
AAS 12 – 339
Formation Flying Dynamics Analysis by Means of a Virtual Multibody Approach

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The aim of this paper is to propose the multibody approach as an alternative method for the analysis of the relative motion in a satellite formation and the evaluation of the related control effort. In the suggested implementation the spacecraft are substituted by the joints of a multibody system in which the links, represented as virtual structural elements, reproduce the relative constraints in position and attitude among the platforms. The idea is to consider the commanded, time-varying orientation and length of the links such that the joints will eventually assume the relative geometry which is the formation's target state at a given time. The forces and torques to be provided to the real spacecraft belonging to the formation are related to the reaction torques and forces which are provided at the joints in the corresponding multibody representation. These reactions can be easily computed by available multibody codes, and can be inserted in a standard orbital propagator to compute the dynamical behaviour of a formation and to validate the approach. [View Full Paper]

IAA-AAS-DyCoSS1-06-09
AAS 12 – 340
Fundamental-Solution Guidance for Satellite Relative Motion in Elliptic Orbits

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The motion of a deputy satellite relative to a chief satellite in elliptic orbit can be modeled with linearized time-varying equations. The solutions to these equations are linear combinations of six fundamental solutions, with the proportionality constants representing integrals of the motion. These constants provide a geometric description of the relative motion, showing how it is composed from the six fundamental modes. This paper analyzes maneuver planning for relative motion using the fundamental-solution description. Impulsive burns by the deputy satellite in the radial, transverse, and cross-track directions are related to the changes in amplitude of each fundamental solution. This approach allows for intuitive, geometric maneuver planning for a broad class of formation-flying missions. [View Full Paper]

IAA-AAS-DyCoSS1-06-10
AAS 12 – 341
Switched Strategy and Sliding Mode Algorithm-Based Relative Position Control Method of Electromagnetic Formation Flying

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Considering the strong nonlinearity and coupling of electromagnetic formation, this paper established the relative orbit dynamics in which the currents generating EM force were direct control variables (current-node model). An electromagnetic formation relative position control method based on switched strategy and variable parameters' sliding mode control algorithm was proposed to deal with the deviation of orbital eccentricity, EM force model's uncertainty and control input matrix's peak problem. Applying the knowledge of system uncertainty, we obtained reasonable control parameters of the sliding mode control algorithm with variable parameters; and the input matrix's peak problem due to the setting of free electromagnetic dipoles was solved by switched control strategy. [View Full Paper]

IAA-AAS-DyCoSS1-06-11
AAS 12 – 342
Ultra-Low Earth Orbit Formation Flying Control using Aerodynamic Forces

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In the ultra-low Earth orbit, which height is about 120 km and above, the spacecrafts are highly affected by the aerodynamic forces. The earlier works had done a lot of research on formation-flying control using the aerodynamic drag forces. However, for a plane spacecraft, the aerodynamic lift force is as significant as the drag forces. Free-molecular flow model, a precise model of aerodynamic force on spacecraft is introduced. A new relative motion equation is deduced, based on such aerodynamic model and CW equation. These new nonlinear equations can be used as the precise relative trajectory propagation; meanwhile, a new control method can be designed base on these equations. [View Full Paper]

SESSION 7: ATTITUDE DYNAMICS AND CONTROL II

Chairs: Antonio Elipe, Universidad de Zaragoza, Spain
Anna D. Guerman, University of Beira Interior, Covilhã, Portugal

IAA-AAS-DyCoSS1-07-01
AAS 12 – 343
Parameter Optimization for Stabilizers

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Georgi V. Smirnov, Centre of Physics, Department of Mathematics and Applications, School of Sciences, University of Minho, Campus de Gualtar, Braga, Portugal

The aim of this work is to develop an effective numerical tool oriented to optimization of stabilizer parameters according to different criteria that appear in engineering practice. We formulate a special optimization problem that allows us to determine optimal parameters of a stabilizer. The obtained results are applied to choose parameters of a spacecraft stabilization system. We discuss the choice of optimization criteria comparing the degree of stability objective function, the H_∞ norm of the system transfer matrix, and the minimal "peak" criterion. [View Full Paper]

IAA-AAS-DyCoSS1-07-02
AAS 12 – 344
Small Gain Stability Theory for Matched Basis Function Repetitive Control

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Many spacecraft suffer from jitter produced by periodic vibration sources such as momentum wheels, reaction wheels, or control moment gyros. Vibration isolation mounts are needed for fine pointing equipment. Active control methods directly addressing frequencies of interest have the potential to completely cancel the influence of these disturbances. Typical repetitive control methods initially address all frequencies of a given period. Matched basis function repetitive control individually addresses each frequency, finding error components at these frequencies using the projection algorithm, and can converge to zero error, using only frequency response knowledge at addressed frequencies. This results in linear control laws but with periodic coefficients. Frequency domain raising produces a time invariant pole/zero model of the control law. A small gain stability theory is developed, that exhibits very strong stability robustness properties to model error. For convergence to zero tracking error it needs only knowledge of the phase response at addressed frequencies, and it must be known within an accuracy of ±90 degrees. Controllers are then designed by pole-zero placement, bypassing the complexity of original periodic coefficient equations. Compared to the usual repetitive control approaches, the approach here eliminates the need for a robustifying zero phase low pass filter, eliminates the need for interpolation in data, and handles multiple unrelated frequencies easily and naturally. [View Full Paper]

IAA-AAS-DyCoSS1-07-03
AAS 12 – 345
Active Magnetic Attitude Control System for Sun-Pointing of a Spin-Stabilized Satellite Without Initial Detumbling

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The angular motion of an axisymmetrical satellite equipped with the active magnetic attitude control system is considered. Dynamics of the satellite is analytically studied on the whole control loop. Two coarse sun-pointing algorithms and nutation damping are studied. Fine sun-pointing algorithm is implemented last. Two different algorithms are proposed. Active magnetic attitude control system time-response with respect to its parameters is analyzed, orbit inclination is of particular interest. Numerical simulation is carried out. [View Full Paper]

IAA-AAS-DyCoSS1-07-04
AAS 12 – 346
A Hybrid Attitude Controller Consisting of Electromagnetic Torque Rods and an Active Fluid Ring

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In this paper, a novel hybrid actuation system for satellite attitude stabilization is proposed along with its feasibility analysis. The system considered consists of two magnetic torque rods and one fluid ring to produce the control torque required in the direction in which magnetic torque rods cannot produce torque. A mathematical model of the system dynamics is derived first. A controller is then developed to stabilize the attitude angles of a satellite equipped with the above-mentioned set of actuators. The effect of failure of the fluid ring or a magnetic torque rod is examined as well. It is noted that the case of the failure of the magnetic torque rod whose torque is along the pitch axis is the most critical, since the coupling between the roll or yaw motion and the pitch motion is quite weak. The simulation results show that the control system proposed is quite fault tolerant. [View Full Paper]

IAA-AAS-DyCoSS1-07-05
AAS 12 – 347
Full Magnetic Satellite Attitude Control Using ASRE Method

Antonio L. Rodriguez-Vazquez and **Maria A. Martin-Prats**, Electronic Engineering Department, Universidad de Sevilla, Spain; **Franco Bernelli-Zazzera**, Aerospace Engineering Department, Politecnico di Milano, Italy

This work introduces a full magnetic control scheme for satellite attitude control. It is particularized for a nadir pointing spacecraft. A new model which includes the satellite attitude dynamics and kinematics considering the magnetic field of the Earth is presented. The model is written in the State-Dependent-Coefficient (SDC) form. In addition, the control problem is formulated by using the Approximating Sequence of Riccati Equation algorithm and solved as a two point boundary value problem. The proposed model and the control technique have been satisfactorily validated by simulation results. [View Full Paper]

IAA-AAS-DyCoSS1-07-06
AAS 12 – 348
Attitude Control for Small Satellites Using Rotation Angles

Teodor-Viorel Chelaru, **Adrian-Mihail Stoica**, **Cristian Barbu** and **Adrian Chelaru**, University POLITEHNICA of Bucharest, Romania

The paper presents some aspects for calculus model of small satellites attitude control. The satellite nonlinear model presented will be with six degrees of freedom. As novelty, the rotation angles for describing the kinematical equations will be used. To highlight the advantage of these parameters, kinematical equations will be described also by using Euler's angles and Hamilton's quaternion. Two attitude control cases will be analyzed: the reaction wheels and micro thrusters. The results will be used in project European Space Moon Orbit – ESMO founded by European Space Agency in which University POLIEHNICA of Bucharest is involved. [View Full Paper]

IAA-AAS-DyCoSS1-07-07
AAS 12 – 349
Robust Control of the Advanced Solid Rocket Launcher

Yasuhiro Morita, Space Flight Systems, ISAS/JAXA, Sagamihara, Kanagawa, Japan

The Epsilon solid rocket launcher proceeded to the full development phase in August 2010 and its first launch is officially declared to be conducted in 2013 to carry a space telescope satellite SPRINT-A. The concept of the vehicle, the next generation launch system, requires a simpler launch system and better user friendly interface than its predecessor, M-V in order to provide small satellites with an efficient launch. Such innovation significantly affects the architecture of the guidance and control system. This paper describes the robust control of the Epsilon rocket launcher. [View Full Paper]

IAA-AAS-DyCoSS1-07-08
AAS 12 – 350
Hybrid Methods for Determining Time-Optimal, Constrained Spacecraft Reorientation Maneuvers

Robert G. Melton, Department of Aerospace Engineering, Pennsylvania State University, University Park, Pennsylvania, U.S.A.

Time-optimal spacecraft slewing maneuvers with path constraints are difficult to compute even with direct methods. This paper examines the use of a hybrid, two-stage approach, in which a heuristic method provides a rough estimate of the solution, and that serves as the input to a pseudospectral optimizer. Three heuristic methods are examined for the first stage: particle swarm optimization (PSO), differential evolution (DE), and bacteria foraging optimization (BFO). In this two-stage method, the PSO-pseudospectral combination is approximately three times faster than the pseudospectral method alone, and the BFO-pseudospectral combination is approximately four times faster; however, the DE does not produce an initial estimate that reduces total computation time. [View Full Paper]

IAA-AAS-DyCoSS1-07-09
AAS 12 – 351
Using the State-Dependent Riccati Equation and Kalman Filter Techniques to Design a Satellite Attitude Control Simulator

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Victor M. R. Arena, Federal University of ABC, Santo André – SP, Brazil

Satellite Attitude Control System (SACS) design is a high cost and risk task, the control hardware and software properly designed using simulator can dramatically minimize space mission costs and risks by reducing the errors that would be transmitted to the next phase of the project. However, experimental satellite dynamics and control on ground test is difficult because of the influences of gravity and friction. Air bearing laboratory prototypes provides a very low-torque environment for investigation of satellite attitude dynamics and control problems. The Space Mechanics and Control Division (DMC) of INPE is constructing a 3D simulator to supply the conditions for implementing and testing satellite hardware and software. The 3D simulator can accommodate various satellites components; like sensors, actuators, computers and its respective interface and electronic. Depending on the manoeuvre the 3D simulator plant can be highly non-linear and if its inertia parameters are not well determined the plant can also present some kind of uncertainty. As a result, controller designed by linear control technique can have its performance and robustness degraded. This paper presents the application of the State-Dependent Riccati Equation (SDRE) method in conjunction with Kalman filter to design and test an attitude control algorithm for a 3D satellite simulator. The SDRE method is the nonlinear counterpart of LQR method with the design advantage of tuning the state and input penalty matrices as functions of states. The control strategy is based on gas jets and reaction wheel torques to perform large angle manoeuvre in three axes. Initially, a simple comparison between the LQR and SDRE controller is performed. The Kalman filter technique is used to deal with the noise in process and measurements as well as the incomplete state information. Simulation has shown the performance and robustness of the SDRE controller applied for angular velocity reduction associated with stringent pointing requirement. The investigation served to validate the numerical model and to verify the functionality of the entire simulator system. [View Full Paper]

IAA-AAS-DyCoSS1-07-11
AAS 12 – 352
Stable Design of Attitude Control for a Spacecraft

Mostafa Bagheri, **Mansour Kabganian** and **Reza Nadafi**, Amirkabir University of Technology, Tehran, Iran

The three-axis attitude control design based on Lyapunov stability criteria to stabilizing the spacecraft and orients it to desired attitude is presented in this paper. This attitude control system is assumed to have four reaction wheels with optimal arrangement. The reaction wheels are located in square pyramidal configuration. Control system inputs are attitude parameter in the quaternion form and the angular velocity of spacecraft and reaction wheels. The controller output is the torque required to eliminate error. In this study, actuators (reaction wheels) are modeled and required torque for attitude maneuver is converted to voltage of actuators. Armature voltage and armature current is limited to 12 volts and 3 amps respectively. Also, each wheel has an angular velocity limit to 370 rad/sec. Numerical simulations indicate that the spacecraft reaches desired attitude after 34 seconds and show the reliability of mentioned configuration with respect to actuator failure. The results show that in case of failure of one reaction wheel, the spacecraft can reach desired attitude but needs more time. Moreover, results demonstrated the controller robustness against parameter variation and disturbances. It is robust against with up to 350% change in spacecraft moment of inertia and robust against disturbance up to 0.0094 N.m that is equal 38% in comparison with the allowable reaction wheel capacity. [View Full Paper]

SESSION 8: ORBITAL DYNAMICS AND DETERMINATION II

Chairs: Robert G. Melton, Pennsylvania State University, University Park, Pennsylvania, U.S.A.
Paolo Teofilatto, University of Rome, DIAEE, Rome, Italy

IAA-AAS-DyCoSS1-08-01
AAS 12 – 353
Keplerization of Motion in Any Central Force Field

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The paper introduces a unified methodology for the study of bounded motion in central force fields, which serves both for qualitative insights, as well as for the derivation of closed-form vectorial solutions for the equations of motion. The paper offers a full regularization of the equations of motion in a central force field, starting from the polar equations in the plane of motion. A time transformation, as well as a coordinate transformation, are performed together, and the motion is (i) reduced to a Kepler motion in a rotating frame, with respect to a new time variable (ii) regularized further to a harmonic oscillator. In addition, some new results pertaining to the existence of a Laplace-Runge-Lenz vector in a central-force motion are presented. [View Full Paper]

IAA-AAS-DyCoSS1-08-02
AAS 12 – 354
Stable Artificial Equilibrium Points in the Mars-Phobos System

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The existence of stable equilibrium regions in the CRTBP under constant thrust acceleration has been pointed out recently. This article analyses the case of the Mars-Phobos system, in which stable hovering can be obtained for a spacecraft coorbiting with the Moon at a distance of about 80 km from its center with less than 15 micro-g of constant acceleration. The system stability is investigated analytically and verified with a full numerical model accounting for all relevant perturbations. [View Full Paper]

IAA-AAS-DyCoSS1-08-03
AAS 12 – 355
Orbital Characteristics of Artificial Satellites around Planetary Satellites

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The interest for space missions toward planetary satellites and small bodies of the solar system has increased in the last decades. Due to the scientific purposes of the missions, special orbits are desirable. In this paper, conditions to get stability of frozen orbits, polar orbits, low inclination orbits around planetary satellites are analyzed taking into account the non-uniform distribution of the mass of the central body and the influence of the perturbations due to a massive body in elliptical orbit. An analytical theory using the averaged model is presented. Applications were done by performing numerical integrations of the analytical equations developed. We use the single-averaged model because it is more realistic, since it does not eliminate the term due to the equatorial ellipticity of the planetary satellite as done on the double-averaged problem. Artificial satellites orbiting the Moon and Europa are considered. For the Moon, we observed that, for low altitude artificial satellites, the perturbations help to control the time variation of the eccentricity, mainly for inclinations near 90°. Considering the long period disturbing potential, using the single-averaged analytical model, we found low-altitude, near-polar orbits that, in general, have short lifetimes for Europa and long lifetimes for the Moon. However, through analysis and simulations, we found frozen orbits at low-altitude, with low-inclination and long lifetimes for the case of the satellite Europa. This choice reduces the maintenance costs of the orbit considerably.
[View Full Paper]

IAA-AAS-DyCoSS1-08-04
AAS 12 – 356
Periodic Solutions in Planetary Annulus Problem

Eva Tresaco and **Antonio Elipe**, Centro Universitario de la Defensa de Zaragoza, Universidad de Zaragoza, Spain; **Andrés Riaguas**, Universidad de Valladolid, Spain

This paper studies the main features of the dynamics around a planetary ring composed by a massive planar annulus and a central body. Based on previous analysis where we analyzed the motion of satellite with infinitesimal mass as attracted by an isolated planar annulus, we raise the question of the dynamics around a central body surrounded by a homogeneous circular annular disk.

For this particular body, we propose to carry out a systematic search of the most relevant solutions periodic orbits, and based on that, describe the in-plane and out-of-plane motion by means of the numerical continuation of a wide number of families of planar and 3-D periodic orbits; thus shedding light on the way the dynamics around a planetary ring is organized.

We should point out that the conclusions we can draw from the phase-space structure are generic and therefore of interest in the context of more realistic models. With the aim of reproducing a more realistic scenery, we will add complexity to our model, considering a variation of the mass proportion between the annulus and the planet and a composition of annuli, in order to predict regions about a ring that are more stable and suitable for a spacecraft to be placed in a scientific exploration mission. Future work is therefore twofold; focused on ring growth and mission planning. [View Full Paper]

IAA-AAS-DyCoSS1-08-05
AAS 12 – 357
Orbital Launch Window for Moon-to-Earth Trajectories

Jingyang Li, **Shengping Gong**, **Hexi Baoyin**, **Junfeng Li** and **S. Y. Yim**,
School of Aerospace, Tsinghua University, Beijing, China

To support China's manned lunar landing mission requirements of high-latitude landing and anytime return, i.e., the capability of safely returning the crew exploration vehicle at any time from any lunar parking orbit, an orbital launch window for Moon-to-Earth return has been established. The launch window is a certain time interval during which the transearth injection may occur and result in a safe lunar return to the specified landing site on the surface of the Earth. Using the patched conic technique, an analytical design method for determining the transearth trajectories is developed with a finite sphere of influence model. Orbital launch window has been established to study the mission sensitivities to transearth trip time and energy requirement, and also to provide the basis for the preparation of an orbital launch timetable compatible with lunar missions and reentry conditions requirements. The results presented here are limited to a single impulsive maneuver. The difference between the results of the analytical model and high-fidelity model is compared. This difference is relatively small and can be easily eliminated by a simple differential correction procedure. The solution can also be used to serve as an initial estimate for future optimization procedures.
[View Full Paper]

IAA-AAS-DyCoSS1-08-06
AAS 12 – 358
Detecting Invariant Manifolds using Hyperbolic Lagrangian Coherent Structures

Daniel Pérez, Departament de Matemàtica Aplicada i Anàlisi, Universitat de Barcelona, Spain; **Gerard Gómez**, IEEC & Departament de Matemàtica Aplicada i Anàlisi, Universitat de Barcelona, Spain; **Josep J. Masdemont**, IEEC & Departament de Matemàtica Aplicada I, ETSEIB, Universitat Politècnica de Catalunya, Barcelona, Spain

Using as reference test model the Planar Circular Restricted Three Body Problem, this paper explores its Lagrangian Coherent Structures, as well as its Hyperbolic Lagrangian Coherent Structures. The purpose is to identify stable and unstable manifolds acting as separatrices between orbits with different qualitative behaviour and, therefore, relevant to the dynamics of the problem. Particular attention is given to the manifolds associated to the collinear libration points and to the practical stability regions around the triangular equilibrium points. [View Full Paper]

IAA-AAS-DyCoSS1-08-07
AAS 12 – 359
Universal Functions in the Study of The Relative Orbital Dynamics

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Vladimir Martinusi, Distributed Space Systems Laboratory, Faculty of Aerospace Engineering, Technion – Israel Institute of Technology, Haifa, Israel

The closed-form solution to the problem of the relative motion in gravitational fields is expressed with the help of the universal functions. The full nonlinear model of the relative motion is considered, and no linearization or approximation assumptions are made. The results are free of singularities and they hold for any reference and targeted orbits, as well as for any time scale. A unified way to propagate the relative orbit with respect to time is introduced, by making use of the solution to a generalized Kepler equation. [View Full Paper]

IAA-AAS-DyCoSS1-08-08
AAS 12 – 360

A Note on the Dynamics around the $L_{1,2}$ Lagrange Points of the Earth–Moon System in a Complete Solar System Model

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In this paper we study the dynamics of a massless particle around the $L_{1,2}$ libration points of the Earth-Moon system in a full Solar System gravitational model. The study is based on the analysis of both the periodic and quasi-periodic solutions around the two collinear equilibrium points, whose computation is implemented using as initial seeds the libration point orbits of Circular Restricted Three Body Problem, determined by Lindstedt-Poincaré methods. In order to do these analysis, an effective algorithm is proposed which, being capable of refining large time-span libration point orbits in real ephemeris, is an iterative combination of a multiple shooting method with a detailed Fourier analysis of the orbits computed with the multiple shooting. [View Full Paper]

IAA-AAS-DyCoSS1-08-10
AAS 12 – 361

Numerical Method for Computing Quasi-Periodic Orbits and Their Stability in the Restricted Three-Body Problem

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Invariant manifolds in the restricted three-body problem are a powerful tool for the design of spacecraft trajectories. This work presents an approach to compute families of quasi-periodic orbits and their linear stability via a stroboscopic map. The approach includes the generation of stable and unstable manifolds from hyperbolic quasi-periodic orbits. Including quasi-periodic orbits along with periodic orbits in the design space offers additional low-energy transfer options. Both the circular and elliptic restricted three-body problems are considered. [View Full Paper]

SESSION 9: SPACECRAFT GUIDANCE, NAVIGATION AND CONTROL II

Chair: Ijar M. da Fonseca, INPE, DMC, São José dos Campos, SP, Brazil

IAA-AAS-DyCoSS1-09-03

AAS 12 – 362

A Ground Facility to Test GNC Algorithms and Sensors for Autonomous Rendezvous and Docking

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This paper presents the project of a GNC system for a ground test-bed rendezvous and docking demonstrator for ground operations and the related rendezvous and docking (RV&D) simulator application, developed within the STEPS regional project (Systems and Technologies for Space Exploration). The test-bed system is a flat floor where two scaled vehicles, one active chaser and one "semi-active" target, can perform rendezvous and docking maneuvers floating on the plane with pierced plates as lifting systems. The GNC system is designed to work both with inertial and non-inertial reference frame systems, receiving signals from various navigation sensors (including a vision system) and combining them with a Kalman filter. A PID control law and PW modulators are used to command the cold gas thrusters of the chaser, and to follow an assigned trajectory with its specified velocity profile. The design of the GNC and its architecture will be detailed in the paper, including a performance analysis based on simulated. A complete description of the integrated subsystems will also be presented.
[View Full Paper]

IAA-AAS-DyCoSS1-09-04

AAS 12 – 363

Hardware-in-the-Loop Rendezvous Simulation Involving an Autonomous Guidance, Navigation and Control System

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The rendezvous process is a key technology in multi-spacecraft missions like on-orbit servicing missions. An active spacecraft (chaser) approaches a passive spacecraft (target) in its orbit by performing controlled orbit and attitude maneuvers. The paper presents an autonomous guidance, navigation and control system for rendezvous using a monocular camera as vision-based sensor for relative navigation. Image processing algorithms and navigation filters are employed to get accurate information about the relative position and attitude between the two spacecrafts. The rendezvous sensor and the entire GNC system is tested and verified at DLR's robotic-based test bed European Proximity Operations Simulator 2.0. [View Full Paper]

IAA-AAS-DyCoSS1-09-05
AAS 12 – 364
Differential Drag Spacecraft Rendezvous Using an Adaptive Lyapunov Control Strategy

David Pérez and **Riccardo Bevilacqua**, Mechanical, Aerospace and Nuclear Engineering Department, Rensselaer Polytechnic Institute, Troy, New York, U.S.A.

This paper introduces a novel Lyapunov-based adaptive control strategy for spacecraft maneuvers using atmospheric differential drag. The control forces required for rendezvous maneuvers at low Earth orbits can be generated by varying the aerodynamic drag affecting each spacecraft. This can be accomplished, for example, by rotating dedicated sets of drag panels. Thus, the relative spacecraft motion can be controlled without using any propellant since the motion of the panels can be powered by solar energy. A novel Adaptive Lyapunov Controller is designed, and a critical value for the relative drag acceleration that ensures Lyapunov stability is found. The critical value is used to adapt the Lyapunov controller, enhancing its performance. The method is validated using simulations in the Analytical Graphics Incorporated's Satellite Tool Kit software. The results show that the Adaptive Lyapunov technique outperforms previous control strategies for differential drag based spacecraft maneuvering. [View Full Paper]

IAA-AAS-DyCoSS1-09-07
AAS 12 – 365
Coupled Position and Attitude Control of a Spacecraft in the Proximity of a Tumbling Target

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Coupled position and attitude control of a spacecraft in the close proximity of a tumbling target to achieve the desired position and attitude alignment using the state-dependent Riccati equation tracking method is presented. The equation of motion of a spacecraft that performs translational and rotational maneuvers simultaneously is highly nonlinear and coupled. A spacecraft must be able to perform position and angle maneuvers simultaneously with sufficient accuracy in a short time. A kinematically coupled spacecraft motion model is newly derived and established to describe the relative position about the feature points on the target and spacecraft bodies. Numerical results show that this control method achieves good tracking performance in the presence of the kinematic coupling. [View Full Paper]

IAA-AAS-DyCoSS1-09-09
AAS 12 – 366
Observer-Based Finite Time Control for Proximity to Target Spacecraft

Shunan Wu, **Zhaowei Sun** and **Juntian Si**, Research Center of Satellite Technology, Harbin Institute of Technology, Harbin, China; **Xue Ma**, School of Aerospace, Tsinghua University, Beijing, China

The finite time control for proximity to target spacecraft is investigated in this paper. The relative motion dynamics for the chaser spacecraft and target spacecraft is firstly proposed. Then a finite time controller, based on a novel fast terminal sliding mode approach, is designed to achieve above control objective. The stability and convergence of the closed-loop system with the property of finite time are discussed by Lyapunov method. The escape maneuver of target spacecraft is further considered, and an observer-based modified finite time controller is proposed to deal with this problem. Numerical simulations are finally provided to illustrate the performance of the proposed controllers. [View Full Paper]

IAA-AAS-DyCoSS1-09-10
AAS 12 – 367
Image Based Control of a Free Flying Platform

Marco Sabatini and **Giovanni B. Palmerini**, DIAEE, Università di Roma "La Sapienza," Rome, Italy; **Riccardo Monti** and **Paolo Gasbarri**, DIMA, Università di Roma "La Sapienza," Rome, Italy

A free floating platform is realized with a pneumatic suspension system which enables a bi-dimensional test of complex space operations, such as rendezvous and docking. The platform is equipped with an IMU and actuated via cold gas thrusters. A target is acquired by an on-board camera and the image is processed for evaluating the control actions needed to reach it. A special effort will be devoted to the reduction of the computational load for the image processing, because of the limited on-board computational resources. A technique for determining the relative position and velocity with respect to target using the same visual device is proposed and realized. The novel algorithms and relevant experimental results are presented. [View Full Paper]

SESSION 10: SPACE STRUCTURES AND TETHERS

Chairs: Harijono Djojodihardjo, Universiti Putra Malaysia (UPM), Serdang, Selangor, Malaysia

Ivan Kosenko, Dorodnitsyn Computing Center of RAS, Moscow, Russia

IAA-AAS-DyCoSS1-10-01

AAS 12 – 368

Numerical Simulations of an Electrodynamic Tether Deployment from a Spool-Type Reel Using Thrusters

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The amount of space debris is ever increasing, and pollution of the space environment has become a serious problem that can no longer be ignored. Consequently, the active removal of large space debris from crowded economically useful orbits should begin as soon as possible. The Japan Aerospace Exploration Agency has been investigating an active debris removal system that employs highly efficient electrodynamic tether (EDT) technology for orbital transfer. This study investigates the tether deployment from a spool-type reel using thrusters by means of numerical simulations of an EDT system. The thrusters are used in order to ensure the deployment of a tether with the length of several kilometers. In the simulations using a multiple mass tether model, the dynamics of tether deployment is studied and requirements of thruster needed for the deployment, such as the thrust forces and the periods of thruster activation, are clarified. [View full Paper]

IAA-AAS-DyCoSS1-10-02

AAS 12 – 369

Stable and Unstable Relative Equilibria of Two Tethered Satellites

Hassan M. Asiri, Astronomy Department, Faculty of Science, King Abdulaziz University, Jeddah, Saudi Arabia

A tethered satellite system consisting of two point masses connected by a massless rigid rod is considered. Equations of planar motion for the system moving in a circular orbit around the Earth are derived. Two relative equilibria of the system are obtained on the basis of the augmented Hamiltonian. Stability of relative equilibria is investigated by means of the reduced energy-momentum method. The system tends to be stable only at one relative equilibrium. [View full Paper]

IAA-AAS-DyCoSS1-10-06
AAS 12 – 370
CSI Due to Sloshing Motion on LEO LSS

Ijar M. da Fonseca, Space Mechanics and Control Division, National Institute for Space Research (INPE), São José dos Campos, SP, Brazil; **Peter M. Bainum**, Department of Mechanical Engineering, Howard University, Washington, D.C., U.S.A.

This paper discusses the mathematical modeling approaches to better represent the sloshing dynamics, the effect of sloshing motion on spacecraft system stabilization, the problem of internal energy dissipation associated with rotating spacecrafts, and existing software tools for dynamics analysis of the sloshing problem. The sloshing phenomenon is presented and discussed in the scope of microgravity environment that characterizes the on orbit space vehicles. In this work the LSS physical model is approached by a large tubular platform containing two large and flexible solar arrays and a large water tank. The actuators for the sake of the attitude control are composed by a set of reaction wheels and a set of thrusters. The gravity-gradient torque is considered as the most important disturbing torque acting on the low Earth orbit (LEO) LSS. The mathematical model includes the solar arrays first mode of vibration and the sloshing effect of the large water tank. The sloshing is mathematically represented by a set of equivalent spring-mass systems. The assumed mode method is used for the mathematical modeling of the elastic displacement of a C-F-F-F plate like solar panel. The proportional integral derivative (PID) control approach is used to derive the control law. The whole linear system of equations is simulated via computer by using the MATLAB software package. The sloshing motion is excited to analyze the impact of the sloshing on the flexibility of the solar arrays. The thrusters are fired to control the LSS attitude causing simultaneously structural vibration and fluid excitation. The impact of the attitude control actuation on the structural and fluid excitation is analyzed. On the other hand the simultaneous structural and liquid excitation impact in the control performance is also studied. The results show that the sloshing excites the solar attitude and attitude rates.
[View full Paper]

IAA-AAS-DyCoSS1-10-07
AAS 12 – 371
Quasi-Periodic Motion of a Ground-Based Tethered Sub-Satellite with Attitude

Dongping Jin and **Hao Wen**, State Key Lab of Mechanics and Control of Mechanical Structures, Nanjing University of Aeronautics and Astronautics, Nanjing, China;
Xiaoyu Wang, Structure Technology Department, Institute of Spacecraft System Technology, Beijing, China

The paper reveals the quasi-periodic characteristics of a tethered sub-satellite with attitude by numerical approach and ground-based experiment. The dimensionless ordinary differential equations that govern the dynamics of the tethered satellite system are obtained according to Kane's method first. Numerical simulations show that there exist a quasi-periodic motion and its co-existence in the system. To verify the quasi-periodic motion, afterwards, a test on the quasi-periodic motion is made via a ground-based experimental platform, which is featured by using a combination of air-bearing facilities and on-simulator thrusters to achieve the physical simulation of the gravity gradient field and Coriolis force of tethered satellite on orbit. The experiment results indicate the existence of quasi-periodic motion. [View full Paper]

IAA-AAS-DyCoSS1-10-08
AAS 12 – 372
Second Order Effects of the Flexibility on the Control of a Spacecraft Full-Coupled Model

P. Gasbarri, **R. Monti** and **C. De Angelis**, Department of Mechanical and Aerospace Engineering, University of Rome "La Sapienza," Rome, Italy; **M. Sabatini**, Department of Astronautics, Electric and Energetic Engineering, University of Rome "La Sapienza," Rome, Italy

One of the most important problems for performing a good design of the spacecraft attitude control law is connected to its robustness when some uncertainties are present on the inertial and/or on the elastic characteristics of a satellite. These uncertainties are generally intrinsic on the modeling of complex structures; in the case of large flexible structure can be attributed also to the secondary effects associated to the elasticity. In fact the inertia tensor in general not only depends on the geometric 'fixed' characteristic of the satellite but also on the elastic displacements, which of course modify the 'shape' of the satellite. Usually these terms can be considered of a second order of magnitude if compared with the ones associated to the rigid part of a structure. However the increasing demand on the dimension of satellites due to the presence for instance of very large solar arrays (necessary to generate power) and/or large antennas has as consequence the necessity to investigate in more details their flexibility effects on the global dynamic behavior. In the present paper a methodology based on classical Lagrangian approach coupled with a standard finite element tool has been used to derive the full dynamic equations of an orbiting flexible satellite under the actions of gravity, gravity gradient forces and attitude control. A particular attention has been paid to the study of the effects of flexibility on the inertial terms of the spacecraft which, as well known, influence its attitude dynamic behavior. Furthermore the effects of the attitude control authority and its robustness to the uncertainties on inertial and elastic parameters has been investigated and discussed. [View full Paper]

IAA-AAS-DyCoSS1-10-09
AAS 12 – 373
Modal Parameters Identification of a Two-Dimensional Space Structure Via Visual Based Technique

R. Monti and **P. Gasbarri**, Department of Mechanical and Aerospace Engineering, University of Rome "La Sapienza," Rome, Italy;
M. Sabatini and **G. B. Palmerini**, Department of Astronautics, Electric and Energetic Engineering, University of Rome "La Sapienza," Rome, Italy

In this paper an operational technique for the vibrating condition identification, based on the use of visual systems coupled with OMA (Operational Modal Analysis) is proposed. With respect to other proposed approaches managing flexibility effects, as nets of accelerometers or even GNSS receivers, visual techniques are by far simpler to implement and pose less constraints to the structure design. In fact, the visual features of the space structure can be considered as virtual sensors for the determination of the elastic behavior. The experimental campaign performed on a very flexible plate confirms the possibility to use optical devices for the identification of modal eigenfrequencies in the range of typical large space structures. [View full Paper]

SESSION 11: MISSION DESIGN AND OPTIMIZATION II

Chair: Antonio Prado, INPE - National Institute for Space Research, São José dos Campos, SP, Brazil

IAA-AAS-DyCoSS1-11-01
AAS 12 – 374
Minimum Fuel Multi-Impulsive Orbital Maneuvers Using Genetic Algorithms

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This work aims to calculate transfer trajectories between two coplanar orbits using several impulses, trying to find solutions that minimize the costs related to the fuel consumption required to apply those impulses. The algorithm used here uses a time-free approach and a genetic algorithm as a method for solving the problem. Evolutionary optimization is used to solve the Lambert´s Problem associated with those transfers and searches for the best trajectories within the various possibilities for solving the problem. After that, a numerical algorithm to solve the same transfers is used, but now considering a low thrust maneuver. This type of propulsion system provides large savings in the consumption, at the expense of more complex and longer maneuvers. [View full Paper]

IAA-AAS-DyCoSS1-11-02
AAS 12 – 375
Mission Analysis and Systems Design of a Near-Term and Far-Term Pole-Sitter Mission

Jeannette Heiligers, **Matteo Ceriotti**, **Colin R. McInnes** and **James D. Biggs**,
Advanced Space Concepts Laboratory, Department of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow, Scotland, United Kingdom

This paper provides a detailed mission analysis and systems design of a near-term and far-term pole-sitter mission. The pole-sitter concept was previously introduced as a solution to the poor temporal resolution of polar observations from highly inclined, low Earth orbits and the poor high latitude coverage from geostationary orbit. It considers a spacecraft that is continuously above either the North or South Pole and, as such, can provide real-time, continuous and hemispherical coverage of the polar regions. Being on a non-Keplerian orbit, a continuous thrust is required to maintain the pole-sitter position. For this, two different propulsion strategies are proposed, which result in a near-term pole-sitter mission using solar electric propulsion (SEP) and a far-term pole-sitter mission where the SEP thruster is hybridized with a solar sail. For both propulsion strategies, minimum propellant pole-sitter orbits are designed. In order to maximize the spacecraft mass at the start of the operations phase of the mission, the transfer from Earth to the pole-sitter is designed and optimized assuming either a Soyuz or an Ariane 5 launch. The maximized mass upon injection into the pole-sitter orbit is subsequently used in a detailed mass budget analysis that will allow for a trade-off between mission lifetime and payload mass capacity. Also, candidate payloads for a range of applications are investigated. Finally, transfers between north and south pole-sitter orbits are considered to overcome the limitations in observations due to the tilt of the polar axis that causes the Poles to be alternately situated in darkness. It will be shown that in some cases these transfers allow for propellant savings, enabling a further extension of the pole-sitter mission. [View full Paper]

IAA-AAS-DyCoSS1-11-03
AAS 12 – 376
Station Keeping of a Solar Sail around a Halo Orbit

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Solar sails are a concept of spacecraft propulsion that takes advantage of solar radiation pressure to propel a spacecraft. Although the thrust provided by a solar sail is small it is constant and unlimited. This offers the chance to deal with novel mission concept. In this work we want to discuss the controllability of a spacecraft around a Halo orbit by means of a solar sail. We will describe the natural dynamics for a solar sail around a Halo orbit. By natural dynamics we mean the behaviour of the trajectory of a solar sail when no control on the sail orientation is applied. We will then discuss how a sequence of changes on the sail orientation will affects the sail's trajectory, and we will use this information to derive efficient station keeping strategies. Finally we will check the robustness of these strategies including different sources of errors in our simulations. [View full Paper]

IAA-AAS-DyCoSS1-11-05
AAS 12 – 377
Simple Method for Performance Evaluation of Multistage Rockets

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Multistage rockets are commonly employed to place spacecraft and satellites in their operational orbits. Performance evaluation of multistage rockets is aimed at defining the maximum payload mass at orbit injection, for specified structural, propulsive, and aerodynamic data of the launch vehicle. This work proposes a simple method for a fast performance evaluation of multistage rockets. The technique at hand is based on three steps: (i) the flight path angle at each stage separation is guessed, (ii) the spacecraft velocity is maximized at the first and second stage separation, and (iii) for the last stage the thrust direction is obtained through the particle swarm optimization technique, in conjunction with the use of the Euler-Lagrange equations and the Pontryagin minimum principle. The coast duration at the second stage separation is optimized as well. The method at hand is intended to generate a near optimal trajectory through a simple, easy-to-implement approach, with the final intent of obtaining a rapid evaluation of the performance of a specified multistage launch vehicle, with reference to different operational orbits. [View full Paper]

IAA-AAS-DyCoSS1-11-06
AAS 12 – 378
Assessment of the Probability of Collision Among Space Objects, 2009 Iridium-Cosmos Collision Case

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This paper deals with the assessment of the collision probability related to some predicted close approaches between two orbiting space objects. This follows that if a critical distance is going to be happened and the probability of its occurrence is exceeding a safe threshold, the time available for collision avoidance maneuver will be obtained. Simplifying assumptions such as a linear relative motion and normally distributed position uncertainties at the predicted closest approach time are applied to estimate the probability of collision using a formulation that takes into account the object sizes, covariance data and the relative distance at the point of closest approach. The computation is performed for close encounter due to 2009 Iridium-Cosmos collision. For cases where we don't know the magnitude of the position uncertainties, the maximum probability can be assessed. For the Iridium-Cosmos collision and the prediction of 1.6 km miss distance using SGP4 and available TLE orbital data, the maximum probability that is obtained was about 2×10^{-6}, which indicates the need of an enhanced orbit determination to achieve an accurate estimation of the collision threat and preventing, if necessary, the hazards thereof. [View full Paper]

IAA-AAS-DyCoSS1-11-07
AAS 12 – 379
Definition and Generation of Multi-Segment Lunar Free-Return Trajectories

Jingyang Li, **Shengping Gong**, **Hexi Baoyin**, **Junfeng Li** and **Xue Ma**, School of Aerospace, Tsinghua University, Beijing, China

To support the mission and trajectory design problems associated with the requirement of safely returning a human crew to the Earth anytime before lunar orbit insertion, a multi-segment lunar free return trajectory is proposed. Differing from hybrid profiles which combine free return and non-free return trajectories, this transfer trajectory consist of free return sections only, while retaining the advantage of hybrid returns. Analysis presented here are limited to two-segment. In the multi-segment profile, the translunar injection is made onto a free-return trajectory with a great perilune altitude, and then the spacecraft performs a transfer maneuver onto a new translunar coast trajectory that has an approximate perilune altitude of 100 km. This new translunar coast trajectory is also designed as a free return trajectory that can perform a safe return. With a finite sphere of influence model, an analytical model of the multi-segment free return trajectories is developed by the matched-conic technique. Characteristics of the injection velocity, flight time and lunar approach inclinations of the multi-segment lunar free returns have been extensively investigated. The results indicated that multi-segment free returns have a wider range of lunar approach inclinations and more freedom can be allowed in the choice of launch window. [View full Paper]

IAA-AAS-DyCoSS1-11-09
AAS 12 – 380
Mission Analysis for Operational Orbit and Transfer Strategy of ESA Proba-3 Mission

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Proba-3 is the third in ESA's series of missions for validating developments in space systems, and consists in a mission that will demonstrate the technologies required for formation flying (FF) of two spacecraft. The spacecraft will be placed on a Highly Elliptical Orbit to obtain reduced perturbation environment around apogee which will allow the execution of several FF demonstrations. The selection of operational orbital elements is a challenging task due to the complexity of orbit evolution, driven principally by Earth and lunisolar gravity perturbations, which make difficult to satisfy specific mission requirements. The operational orbit is reached after a long sequence of maneuvers, which also need to be optimized to satisfy mission constraints while saving propellant mass. The purpose of this paper is to illustrate the results of recent orbit and transfer mission analysis activities, focusing on the relation between mission requirements, system design and perturbation environment, and explaining the methodology followed to reach the current design point. A set of complete trajectories from launch injection to end of mission are reported, providing also relevant data for system design.
[View full Paper]

IAA-AAS-DyCoSS1-11-10
AAS 12 – 381
Optimization of Target Functioning Plans and Constellations of Satellite Observation and Communication Systems

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The general methodology for optimization of operative target functioning plans and constellations of satellite observation (or monitoring) and communication systems is considered in the Preprint. The general problem and applied tasks mathematical statements are given. Methodical approach for such problem and tasks solving and its main aspects are described. Several examples of model optimization tasks are considered: for constellation of 8 different observation spacecrafts, carrying out ecological monitoring of local terrestrial objects during 2 days; for constellations of 5 observation spacecrafts with project parameters of "Rapid Eye" system, carrying out shooting of given territory during 3 or 4 days; for constellations of "Iridium" (66 spacecrafts) and "Teledesic" (288 spacecrafts) global communication systems projects. The results are illustrated and discussed in the Preprint. [View full Paper]

SESSION 12: SATELLITE CONSTELLATIONS AND FORMATION FLYING II

Chairs: David C. Folta, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.
Gerard Gómez, University of Barcelona, Spain

IAA-AAS-DyCoSS1-12-01
AAS 12 – 382
Analysis of Satellite Constellations on Pseudo-Sun-Synchronous, Highly Elliptical Orbits

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For almost continuous coverage of light Earth's areas can be used new pseudo-sun-synchronous, highly elliptic orbits using the critical inclination and orbit apogee in the Earth's hemisphere with coverage areas. In opposite to the classical Molniya-type orbits, the new orbits are synchronized with the solar time (or the solar day) that the apogee time is coincident with the local noon of a coverage area or reference meridian. Qualitative analysis and long-term simulation results for one satellite and constellations with 2-4 satellites in the orbits are presented. For such coverage, the constellations required less satellites than highly elliptical, Molniya-type orbit constellations for continuous zonal or regional coverage. [View full Paper]

IAA-AAS-DyCoSS1-12-02
AAS 12 – 383
Constellation Design for Responsive Revisiting

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Responsive communications or Earth observation missions typically require frequent revisit to any point of the Earth's surface and employ a constellation with two satellites to improve coverage performance. As a new approach to constellation design, a novel constellation is presented by fixing the interval between successive revisits at all latitudes. Analytic and numerical simulations are implemented to illustrate that such a revisiting constellation exists in a large region parameterized by the relative values of right ascension of ascending node and argument of latitude. A global investigation is presented to address the practical time-resolution of the constellation and its topological shape, the existence region, and the relationship to the semi-major axis and inclination.
[View full Paper]

IAA-AAS-DyCoSS1-12-03
AAS 12 – 384
Application of SDRE Technique to Orbital and Attitude Control of Spacecraft Formation Flying

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In this paper a nonlinear control technique for coupled orbital and attitude relative motion of formation flying is presented. Future spacecraft formations will exploit very low inter-satellite range for enhance in-space maneuvers and operations, so high performances in autonomous control will be required. The proposed control system is based on the solution of the *State-Dependent Riccati Equation* (SDRE), which is one of the more promising nonlinear techniques for regulating nonlinear system in all the major branches of engineering. The coupling of the relative orbital and attitude motion is obtained considering the same set of thrusters for the control of both orbital and attitude relative dynamics. In addition, SDRE algorithm is implemented with a timing strategy both for the controller and the proposed nonlinear filter. An up-to-date formation mission, which is ESA Proba-3, constitutes the test-bed for the designed control system. Numerical simulations considering a tracking signal for both orbital and attitude relative maneuver during an operative orbit of the mission are presented. [View full Paper]

IAA-AAS-DyCoSS1-12-04
AAS 12 – 385
Relative Motion Control of Geostationary Satellites in Formation

Vinod Kumar, ISRO Satellite Centre, Bangalore, India and Ph.D. Scholar, Indian Institute of Technology, Bombay, Mumbai, India; **Hari B. Hablani**, Aerospace Department, Indian Institute of Technology, Bombay, Mumbai, India;
R. Pandiyan, ISRO Satellite Centre, Bangalore, India

Currently, ISRO co-locates four satellites at one geo location, and avoids collision between them through ground planning and maneuvers. But in view of the ever increasing demand for geostationary satellites, there exists a need for complete autonomous navigation and control of the satellites in the cluster. Keeping this goal in mind, the Hills-Clohessey-Wiltshire (HCW) equations are used here to model the dynamics of the satellites in formation. It is known that periodic relative motions in local-vertical-local-horizontal reference frame are, respectively, an in-plane ellipse and an out-of plane circle. When perturbations are included, these periodic motions cannot be maintained without control. The controlled motion of a spacecraft in the presence of solar radiation pressure is simulated. Formation architecture is used to exploit favorably the natural perturbations of the orbits from the Earth, the Sun and the Moon, and avoid collision. Since a precise formation control must be accomplished to avoid collision, the position and velocity uncertainties caused by the formulation of formation dynamics should be no more than the high accuracy level of the imaging sensors. A high-fidelity inertial formulation is therefore recommended for the analysis and simulation of relative motion. [View full Paper]

IAA-AAS-DyCoSS1-12-05
AAS 12 – 386
Design of an Earth-Observation Satellite Constellation Via Image Return Time Figure of Merit

Burak Akbulut, **Ahmet Özkan**, **Anıl Özmen**, **Görkem Oktay**, **Erhan Topal**, **Kağan Ataalp** and **Erhan Solakoğlu**, Satellite Systems, Turkish Aerospace Industries Inc., Kazan, Ankara, Turkey

This paper aims to analyze an optimal configuration for a satellite constellation needed for successful completion of an imaging request from a predefined target area. A figure of merit is defined for comparison of different constellation configurations. Different numbers of satellites are analyzed in single and multi orbital planes. Preliminary results show that it is not beneficial to increase the number of satellites in a plane after a certain limit and multi plane approach does not provide significant improvement to results when a target area within a communication cone of a single ground station is considered. [View full Paper]

IAA-AAS-DyCoSS1-12-06
AAS 12 – 387
Constellation Orbits Selection Considering the Interoperability between Different GNSS

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The paper is mainly focused on the orbits selection for the COMPASS global constellation. Two optimized schemes were proposed, for the interoperability with GLONASS and Galileo. Because of the high drifting speed of GPS's orbit planes, it is very difficult to choose a constellation configuration suits for GPS. The altitude 24126km interoperated with Galileo was chosen for the COMPASS global constellation as a candidate scheme, because of the high performance, less perturbation influences, and so on. The Walker 24/3/1: 51.59°, 24126km constellation's performances interoperated with the GPS, GLONASS and Galileo were studied. Great availability improvement was achieved in 35° elevation through the drifting rate design.
[View full Paper]

IAA-AAS-DyCoSS1-12-07
AAS 12 – 388
Preliminary Results of the Vision Based Rendezvous and Formation Flying Experiments Performed During the PRISMA Extended Mission

M. Delpech, **J. C. Berges**, **S. Djalal**, **P. Y. Guidotti**, CNES, Toulouse, France;
J. Christy, Thales Alenia Space, Cannes, France

Through its participation to the nominal phase of the PRISMA technology mission, CNES has successfully demonstrated rendezvous and formation flying techniques based on new radiofrequency metrology system. CNES went a step further by participating to the extended mission phase and performing a complementary experiment in October 2011. CNES implemented a new on-board software including this time vision based navigation using two cameras accommodated on the chaser satellite. A long range camera providing the "target" bearing angles was used to perform vision based rendezvous with a non cooperative object. A close Range camera that can determine the relative 3D position of a cooperative satellite carrying LEDs was further used as a second metrology stage for proximity operations under 30 meters range. Four rendezvous were performed with success from ranges up to 10 km and destinations down to 50 m. Four series of transitions between RF based and VBS based navigation were exercised satisfactorily during tight proximity control to demonstrate the multi-stage metrology system needed for future formation flying missions. The paper presents the results obtained during this extended phase and outlines the preliminary conclusions. [View full Paper]

IAA-AAS-DyCoSS1-12-08
AAS 12 – 389
Integrated Relative Translation and Rotation Control of Spacecraft Formations

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Debasish Ghose and **M. Seetharama Bhat**, Aerospace Engineering, Indian Institute of Science, Bangalore, India

Formation flying of small spacecraft provides a way to improve the resolution by aperture distribution. This requires autonomous control of relative position and relative attitude. The present work addresses the formation control using a PID controller to maintain both relative position and relative attitude. To avoid continuous pulsing due to noise, a dead-band has been provided in the position loop. PID control has been selected to maintain the formation in the presence of unmodeled disturbances. Simulations show that the proposed controller meets the required translational and rotational relative motions even in the presence of disturbances. [View full Paper]

IAA-AAS-DyCoSS1-12-09

AAS 12 – 390

Parametric Optimization of Near-Equatorial Twin-Spacecrafts Trajectory Based on Ground-Track Performance Measure Requirements

Harijono Djojodihardjo and **A. Aq'Grabin A. Gunter**, Aerospace Engineering Department, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia

Parametric optimization study is carried out on Performance Measure for assessing the benefits of relevant ground-track parameters and Instantaneous Overlap Area (IOA) in near earth and near-equatorial twin-satellite formation flying to explore its potential for of spacecraft formation flying as space platform to carry out Tropical Resources and Environment Monitoring mission. The present study also emphasizes two aspects: the dynamics of relative motion of multiple spacecrafts and the desirable ground tracks beneficial for tropical environmental and resources monitoring missions. Relative motion dynamics incorporating Clohessy-Wiltshire Equation for circular orbits is used as a reference. Related to the relevance of Ground-Track based characteristics and to optimize computational efforts, the performance metric is synthesized as a trade off between exact definition and intuitive judgment.

Keywords: orbital mechanics, spacecraft formation flying, tropical remote sensing

[View full Paper]

IAA-AAS-DyCoSS1-12-10
AAS 12 – 391
Precision Control System for Inner-Formation Gravity Field Measurement Satellite System

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The inner-formation gravity field measurement satellite system is a novel concept and can finish the high precision gravity field measurement. The inner-formation system is composed of the outer satellite and the inner satellite which shielded in the cavity center of the outer satellite and without connection with the outer satellite. And the control of the inner-formation system can treat as a formation of zero size using the inner satellite as reference. In order to finish the in-orbit, real time control of the inner-formation system and satisfy the performance requirements of gravity field measurement in low orbit, the control system of the inner-formation system need provide precision control. Through compensating most of air drag, the precision control system can reduce the disturbance of the feedback controller. The paper proposed a hybrid control scheme includes feed forward and feedback control, then the nonlinear model predictive control method with disturbance compensation is also proposed which the disturbance estimation method is unscented Kalman filter. The precision control system can finish the integrate control of attitude and orbit for the inner-formation gravity field measurement satellite system with limited inputs, and the maintenance accuracy of the relative position is not surpass 0.05cm, the attitude stabilization control accuracy is better than 0.03°, which meet the strong constraints of the relatively position and high attitude stabilization required by the gravity field measurement mission. The precision control system designed for inner-formation system can ensure that the influence caused by different disturbances is controlled in 10^{-11}g level. [View full Paper]

IAA-AAS-DyCoSS1-12-11
AAS 12 – 392
Study of On-Orbit Separation Schemes for Configuration Initialization of Fractionated Spacecraft Cluster Flying

Jiang Chao, **Wang Zhaokui** and **Zhang Yulin**, School of Aerospace, Tsinghua University, Beijing, China

Using one Multi-satellite Deployment System to provide each module once velocity increment, the fractionated spacecraft cluster configuration can be formed without module maneuver. At first, the dynamics of cluster configuration initialization was analyzed, based on which the constraints of separation initialization schemes design were given. Then, according to various of separation parameters, a series of separation initialization schemes were designed. At last, the separation error affect and the cluster flying natural evolution are simulated in the high precision formation flying simulation environment, and the best separation initialization scheme is selected by comparing of the simulation results. [View full Paper]

SESSION 13: ATTITUDE DYNAMICS AND CONTROL III

Chair: Arun K. Misra, McGill University, Montreal, PQ, Canada

IAA-AAS-DyCoSS1-13-02

AAS 12 – 393

Attitude Control Software Solution for a Big Solar Panel on LEO Orbit

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The future of the alternative energy is in the space: the solar power is one of the best candidates to help human demand of energy. In space, the capture of the solar energy will have benefits compared to the Earth capture. The solution could be solar panels orbiting as independent spacecrafts, receiving solar energy, storing it and resending to the ground. Assuming the possibility of these solar-array-space station orbiting on LEO, one of the main problem would be the orientation for the best capture of the sun beams, and even the possibility of maneuvers. In this paper it is presented a software that can control the attitude of this solar-array-station. This is based on a simulation of an active control using three reaction wheels designed in the center of the structure that can control the panel. In the paper, as description of the software, are presented: the proportional derivative control, how the wheels physically work, some topics of the software as the integration, the orbit, the reference systems (sun, body, target) and others. It is shown also a part in which there is a panoramic view of the design of the control, of the masses, maximum torques and so on, with a particular focus on wheels sizing and velocities of them. The target of the control is the attitude of the panel, orbiting on LEO; in this study the software is used for some typical maneuvers: the movement from a wrong orientation to the correct one for the best sun-position, a continuous sun chasing during a simulation of twenty-five days. Also some real situations are implemented as: debris impact and/or external torques-forces, and the interaction between the panel and the sun pressure during a complete orbit from dark side to light side. This paper is only a first step on the study of the implementation of the software, in fact some key points are left out. Further it will be implemented in the simulation of the attitude of this panel the interaction with the Earth magnetic field, the interaction with the atmosphere at different altitude (aerodynamics study), and the flexibility of the structure and the control of it during the maneuvers. [View full Paper]

IAA-AAS-DyCoSS1-13-03
AAS 12 – 394
Attitude and Orbit Control System (AOCS) Design for Astrosat

J. S. Khoral, **P. Natarajan**, **R. Pandiyan**, **K. M. Bharadwaj** and **K. Parameswaran**, ISRO Satellite Centre, Vimanapura Post, Bengaluru, India

Astrosat is a stellar oriented satellite for Astronomical observations. Astrosat will be launched using the Polar Satellite Launch Vehicle (PSLV) into an orbit of altitude ~ 650 km and an inclination of about 8° The scientific goals will be met by the various payloads namely, Ultra Violet Imaging Telescope (UVIT), Large Area Xenon filled Proportional Counter (LAXPC), Soft X-ray Telescope (SXT), Cadmium Zinc Telluride detector (CZT) and Scanning Sky Monitor (SSM). The first four payloads operate in pointing mode whereas the SSM operates in step & scan mode. This paper presents a novel result on avoiding the sun – when performing rest-rest reorientation maneuvers via the Euler rotation theorem – in the FOV of the sensitive payloads. [View full Paper]

IAA-AAS-DyCoSS1-13-04
AAS 12 – 395
Three Axes Reaction Thrusters Attitude Control System During Trajectory Manoeuvers for ESMO

Claudiu-Lucian Prioroc and **Mihaela Raluca Stefanscu**, Aerospace Engineering, University "Politehnica" of Bucharest, Romania

The attitude inertial control system during lunar orbit insertion for ESMO has been designed. Four attitude control thrusters and MEMS rate sensors have been chosen as control hardware of the satellite. The system has been designed to minimize the delta-V error. Modelling of the spacecraft attitude control hardware, sloshing, main engines, attitude dynamics and kinematics is presented with simulation results validating the attitude control system. [View full Paper]

IAA-AAS-DyCoSS1-13-05
AAS 12 – 396
Dynamical Attitude Model for Gaia: Micro-Meteoroids and Clanks

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The Dynamical Attitude Model (DAM) is a simulation developed to achieve a detailed understanding of the Gaia spacecraft attitude. This simulation takes into account some disturbances and considers as well internal hardware components controlling the satellite like the AOCS (Attitude and Orbit Control System), sensors (a star tracker and an angular rate sensor attached to the main instrument), and micro-Newton thrusters. This contribution provides a brief description of DAM and an analysis of some effects on Gaia's attitude, such as characteristic profiles of micro-meteoroid impacts and clanks (discontinuities in the attitude while the angular rate is constant). [View full Paper]

IAA-AAS-DyCoSS1-13-11
AAS 12 – 397

Attitude Determination and Control of Pratham, Indian Institute of Technology Bombay's First Student Satellite

Sanyam S. Mulay, **Yashovardhan S. Chati**, **Vaibhav V. Unhelkar**, **Avnish Kumar**, and **Hari B. Hablani**, Department of Aerospace Engineering, Indian Institute of Technology, Bombay, Mumbai, India; **Jaideep Joshi**, Centre for Ecological Sciences, Indian Institute of Science, Bangalore, Bengaluru, India; **Saptarshi Bandyopadhyay**, Department of Aerospace Engineering, University of Illinois at Urbana-Champaign, U.S.A. **Shashank Tamaskar**, School of Aeronautics and Astronautics, Purdue University, West Lafayette, Indiana, U.S.A.; **Mallesh Bommanahal**, National Aerospace Laboratory, Bengaluru, India; **Chaitanya Talnikar**, Department of Chemical Engineering, Indian Institute of Technology, Bombay, Mumbai, India

This paper describes the attitude determination and control sub-system of 'Pratham', a microsatellite being built by the students of Indian Institute of Technology Bombay. Student satellites, such as Pratham, usually have limited sensing, computational and communication capability, motivating the need of autonomous and computationally efficient algorithms. Methods for determining and controlling the attitude with minimal computation load and without any ground support to achieve the desired pointing accuracy are presented. A three axis magnetometer, six 2-π sun sensors and a single frequency GPS receiver are used as the on-board sensors for attitude determination using a single frame method. The attitude controller is designed to achieve an accuracy of 10 degrees in nadir pointing using three orthogonal magnetorquers. Performance of the algorithms is verified through closed loop simulations involving models of the satellite environment, dynamics, actuators and sensors. Lastly, preliminary results of the real time On-board Computer in Loop Simulations are presented. [View full Paper]

SESSION 14: OPTIMAL CONTROL IN SPACE FLIGHT DYNAMICS

Chairs: Bernd Dachwald, FH Aachen University of Applied Sciences, Germany
Kathleen C. Howell, Purdue University, West Lafayette, Indiana, U.S.A.

IAA-AAS-DyCoSS1-14-03
AAS 12 – 398
A Method to Solve Nonlinear Optimal Control Problems in Astrodynamics

Francesco Topputo and **Franco Bernelli-Zazzera**, Dipartimento di Ingegneria Aerospaziale, Politecnico di Milano, Italy

A method to solve nonlinear optimal control problems is proposed in this work. The method implements an approximating sequence of time-varying linear quadratic regulators that converge to the solution of the original, nonlinear problem. Each sub-problem is solved by manipulating the state transition matrix of the state-costate dynamics. Hard, soft, and mixed boundary conditions are handled. The presented method is a modified version of an algorithm known as “approximating sequence of Riccati equations”. Sample problems are treated to show the effectiveness of the method, whose limitations are also discussed. [View full Paper]

IAA-AAS-DyCoSS1-14-06
AAS 12 – 399
Power-Limited Solar Electric Propulsion Trajectory Optimization

Yang Chen, **Hexi Baoyin** and **Junfeng Li**, School of Aerospace, Tsinghua University, Beijing, China

The Solar Electric Propulsion trajectory optimization with power constraints is investigated. A relatively realistic thruster model is used to construct the power constraints. The fuel-optimal control problem is solved via an indirect method. The optimal control laws of the thruster input power and the thrust direction are derived. The solar array power varies with the heliocentric distance, and accordingly the Euler-Lagrange equations hold two different forms. Therefore, the detection of heliocentric distance with fixed step integration is presented to ensure accuracy. Moreover, The normalization of initial costates and switching function detection are employed to improve computational efficiency and accuracy. The trajectory towards Apophis is discussed to substantiate the efficiency of these techniques. [View full Paper]

IAA-AAS-DyCoSS1-14-07
AAS 12 – 400
Analysis of Interplanetary Solar Sail Trajectories with Attitude Dynamics

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We present a new approach to the problem of optimal control of solar sails for low-thrust trajectory optimization. The objective was to find the required control torque magnitudes in order to steer a solar sail in interplanetary space. A new steering strategy, controlling the solar sail with generic torques applied about the spacecraft body axes, is integrated into the existing low-thrust trajectory optimization software *InTrance*. This software combines artificial neural networks and evolutionary algorithms to find steering strategies close to the global optimum without an initial guess. Furthermore, we implement a three rotational degree-of-freedom rigid-body attitude dynamics model to represent the solar sail in space. Two interplanetary transfers to Mars and Neptune are chosen to represent typical future solar sail mission scenarios. The results found with the new steering strategy are compared to the existing reference trajectories without attitude dynamics. The resulting control torques required to accomplish the missions are investigated, as they pose the primary requirements to a real on-board attitude control system.
[View full Paper]

IAA-AAS-DyCoSS1-14-08
AAS 12 – 401
Automatic Control Systems for ESMO Satellite Using LQR Control Strategy

Mihaela Raluca Stefanescu and **Claudiu Lucian Prioroc**, Department of Aerospace Engineering, University “Politehnica” of Bucharest, Romania

This paper studies the attitude control of ESMO (European Student Moon Orbiter) satellite. ESMO is a European project developed by ESA that has the purpose of initializing young students with ESA terminology, teamwork and not least with space research. As well aspects of attitude representation and kinematics and dynamics in terms of quaternion and angular rates will be finding in this paper. The control system is based on the Linear Quadratic Regulator (LQR) theory. [View full Paper]

IAA-AAS-DyCoSS1-14-09

AAS 12 – 402

High Order Optimal Feedback Control of Low-Thrust Orbital Transfers with Saturating Actuators

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Optimal feedback control is classically based on linear approximations, whose accuracy drops off rapidly in highly nonlinear dynamics. Several nonlinear optimal feedback control strategies have appeared in recent years. Among them, differential algebraic techniques have already been used to tackle nonlinearities by expanding the solution of the optimal control problem about a reference trajectory and reducing the computation of optimal feedback control laws to the evaluation of high order polynomials. However, the resulting high order method could not handle control saturation constraints, which remain a critical facet of nonlinear optimal feedback control. This work introduces the management of saturating actuators in the differential algebraic method. More specifically, the constraints are included in the optimal control problem formulation and differential algebra is used to expand the associated optimal bang-bang solution with respect to initial and terminal conditions. Optimal feedback control laws for thrust direction and switching times are again computed by evaluating the resulting polynomials. Illustrative applications are presented in the frame of the optimal low-thrust transfer to asteroid 1996 FG_3. [View full Paper]

SESSION 15: SPACECRAFT GUIDANCE, NAVIGATION, AND CONTROL III

Chairs: Ijar M. da Fonseca, INPE, DMC, São José dos Campos, SP, Brazil
David C. Folta, NASA Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.

IAA-AAS-DyCoSS1-15-01

AAS 12 – 403

Weak Exponential Stability Via Averaging and Applications

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The averaging method is one of the most powerful methods used to analyze differential equations appearing in the study of nonlinear problems. The averaging method has also been successfully applied in control problems, simplifying the equations and study of the systems involved. In this work, applying the averaging method, we study exponential stability of time varying linear control systems. The obtained results are applied to prove the existence of almost closed relative trajectories for formation flying with single-input control. [View Full Paper]

IAA-AAS-DyCoSS1-15-03
AAS 12 – 404
Development and Validation in Real Time Environment of a GNC System for Planetary RV

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This paper describes the design, development and validation in laboratory of a GNC system for autonomous RV in planetary environments. An explicit distinction is made between terminal RV phase, characterized by the close proximity between the two spacecraft, and intermediate RV, in which orbits are quite different and distances up to thousands of km. A dedicated laboratory was developed in parallel, intended to test this GNC system in real time with HW in the loop: a camera used for relative motion measurements. Results from the real time validation campaign in the laboratory are shown and analysed, demonstrating the maturation of the designed system up to a TRL 5.
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IAA-AAS-DyCoSS1-15-04
AAS 12 – 405
Control System Design of Korea Lunar Lander Demonstrator

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In preparation for the lunar exploration program scheduled to be launched during the early 2020s in Korea, lunar lander demonstrator which will be used for developing and demonstrating lunar landing technologies is being developed. Control configuration of the lunar lander demonstrator is determined with the consideration of available technologies and flight requirements. Altitude control by clustering five 200N monopropellant thrusters, and attitude control with eight 3N thrusters are suggested. Control algorithm to follow predefined trajectory is developed using quaternion feedback. Control system configuration and control logic are verified by using computer simulations. Simulation results show that requirements of soft landing required by landing leg components and requirements of attitude control performance can be satisfied with designed control system. Future plan of processor in the loop simulation and actual flight test plan are also introduced. [View Full Paper]

IAA-AAS-DyCoSS1-15-05
AAS 12 – 406
Payload Maximization of LTGL with Normal Force Disturbance

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The purpose of this paper is to study the payload maximization problem with and without normal force disturbance for the development of Taiwan Small Launch Vehicle (TSLV) based on the three-dimensional linear tangent guidance law (LTGL) and the parameter optimization method. As the preliminary study, a nominal trajectory is designed. A launch vehicle model is proposed to be able to insert a 1,000 kg satellite into a 646 km altitude orbit. For the atmosphere, the National Aeronautics and Space Administration (NASA) established model is used. When the mass of payload is increased, either with or without normal force disturbance, the ascent trajectory of the launch vehicle is deviated from the nominal trajectory. The LTGL is then imposed to guide the launch vehicle back to the nominal trajectory. Consequently, the purpose of precise orbit insertion can be achieved. The maximum values of satellite mass obtained are 1,200 kg and 1,070 kg for the cases with and without normal force disturbance, respectively.
[View Full Paper]

IAA-AAS-DyCoSS1-15-08
AAS 12 – 407
Drag Derived Altitude for Improved Navigation Accuracy in Mars Entry Descent and Landing System

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Precise on-board navigation accuracy is a key issue for Mars Entry Descent and Landing Systems. During the entry phase, a probe can rely on the Inertial Navigation System, whose performances are limited by: sensor accuracy, initialization at Mars Entry Interface, platform alignment, instability of vertical channel. The vertical channel stabilization is particularly important and drives the altitude navigation accuracy up to the main parachute deployment. This paper shows that the Drag Derived Altitude technique can be beneficially used in Mars entry scenario to stabilize navigation solution and provide an altitude estimation independently of the Entry Interface conditions.
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